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ON THE AMOUNT OF INTERNAL FRICTION DEVELOPED IN ROCKS DURING DEFORMATION AND ON THE RELATIVE PLASTICITY OF DIFFERENT TYPES OF ROCKS

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INTRODUCTION

At the meeting of the Geological Society of America held in Albany in the year 1900, a brief résumé of the experimental work on the flow of marble carried out by Adams and Nicolson was presented to the Society, and in the discussion which followed the reading of this paper a number of interesting points were suggested by various speakers as worthy of experimental investigation. Among these was one put forward by Dr. G. K. Gilbert, which, in a letter to the authors, he subsequently formulated as follows:

> It has been thought that great pressure breaks down the structure called solidity and so reduces viscosity that very little differential stress is necessary to produce flow. It is thought that the strength of rocks is practically unaffected by pressure, in which case flow should begin only when differential stress equals the crushing strength of the material as conditioned by the temperature. It is certainly conceivable also that the strength of rocks is increased by pressure, so that the production of flow requires differential stress greater than the crushing stress as conditioned by the temperature. I hope your experimentation may be brought to throw light upon this point.

The sense in which certain terms are used in this quotation is not quite clear, but we understand the question put forward by Dr. Gilbert to be as follows:

A unit cube of any rock—granite for instance—is submitted to pressure in a testing machine on the earth's surface. It will give away or break down under a certain load—this is termed its crushing load.

If this cube of rock were imbedded deep within the earth's crust, great pressure would be exerted upon it from all sides. Such being the case, and omitting from consideration the influence of temperature, would the rock (1) be reduced to a condition which approaches fluidity and move at once if the pressure in one direction became slightly greater than that in another? Or (2) would the rock become deformed only when this additional pressure in one direction was equal to its crushing load at the surface? Or (3) would the rock show an increased resistance to deformation and require a much greater additional pressure in one direction to deform it than was required to crush it at the surface?

A few preliminary trials which served to open up the experimental investigation of this problem were undertaken some years ago by Dr. Adams in association with Dr. Ernest G. Coker, then Associate Professor of Civil Engineering at McGill University. Dr. Coker subsequently resigned his position at McGill University to accept the professorship of mechanical engineering and applied mathematics at the Finsbury Technical College in London, and for a time the work was discontinued. Dr. Bancroft, however, some years later coming to McGill University, the investigation was resumed. It has extended over a period of several years. The writers desire to acknowledge their indebtedness to the Carnegie Institute of Washington, the work having been carried out under a grant received from that body.

ROCKS EXAMINED

The following rocks were examined:
White alabaster, Castelino, Italy.
White marble, Carrara, Italy.
Black Belgian marble ("Noir fin").

White dolomite, Cockeysville, Maryland, U.S.A.
Steatite ("Albarine"), Virginia, U.S.A.
Slate, New Rockland, Province of Quebec, Canada.
Sandstone, Cleveland, Ohio, U.S.A.
Granite, Baveno, Italy.
Olivine diabase, Sudbury, Province of Ontario, Canada.

For the purposes of comparison experiments were also conducted with metallic copper and metallic lead.

Detailed petrographical descriptions of these rocks, with the exception of the alabaster, dolomite, steatite, and slate, have been given in a former paper.[1] It is necessary here, therefore, to refer briefly to the character of these four rocks only.

Alabaster, Castelino, Italy.—Under the microscope the rock is seen to be composed of an aggregate of small grains of gypsum which are clear, colorless, and approximately equal in size. The individual grains display a tendency to elongation in one direction, thus giving the rock a very faint foliation. The columns of alabaster used in the experiments were cut from a single uniform block of this rock in such a manner that their longer axes were parallel to this indistinct foliation.

Dolomite, Cockeysville, Maryland, U.S.A.—This is a rather fine-grained, white, granular dolomite, very pure in character and uniform in composition, containing $CaCO_3$ and $MgCO_3$ in almost exactly their molecular proportions. It presents the appearance of a white marble and is extensively quarried as such. Thin sections of the rock, when examined under the microscope, show that it is composed of a mosaic of grains of the mineral dolomite, more or less irregular in shape and varying somewhat in size. Between crossed nicols, they present a uniform extinction or show only the faintest strain shadows. They are very seldom twinned.

Steatite, Virginia, U.S.A.—This steatite is placed on the market under the name of "albarine." The columns employed in the experiments were cut from a perfectly uniform slab of this rock

[1] "An Investigation into the Elastic Constants of Rocks More Especially with Reference to Their Cubic Compressibility," by F. D. Adams and E. G. Coker, The Carnegie Institute of Washington, 1906; see also *American Journal of Science*, XXII (August, 1906).

with dimensions of $10'' \times 11'' \times 1\frac{1}{4}''$. Under the microscope the rock is seen to possess a distinct foliation parallel to the broad surface of the slab. All of the columns were cut from this slab with their longer axes parallel to the foliation. In thin sections under the microscope the rock is seen to be composed chiefly of chlorite, talc and dolomite, numerous small crystals and grains of magnetite, and a few grains of pyrite are also present. The two minerals, chlorite and talc, make up by far the greater portion of the rock, the chlorite being somewhat more abundant than the talc. Both occur as plates and sheaflike aggregates, and both possess a very distinct cleavage parallel to which extinction takes place. The dolomite is present both in large rhombohedral individuals and as small irregular granules which possess a linear arrangement parallel to the foliation of the rock. None of the grains of dolomite show either twinning or strain shadows. Having been cut parallel to the foliation, it is not surprising that the columns of this rock employed in the experiments bulged assymetrically when deformed, and hence a larger number of experiments were made with the steatite than with the other rocks, in order that accurate average results might be secured.

Slate, New Rockland, Quebec, Canada.—This is a typical fine-grained slate, black in color, uniform in character, and possessing an excellent cleavage. By means of a diamond drill cores were taken perpendicular to the cleavage of the slate, and from these the columns of slate used in the experiments were prepared.

Under the microscope this slate is found to be composed essentially of minute flakes of two minerals, one of which is apparently kaolin and the other muscovite. In general, the kaolin is much more abundant than the muscovite, from which it can be distinguished in that it possesses a lower double refraction and is not quite so transparent. Within a few extremely narrow bands of the slate the muscovite preponderates. A few minute grains of quartz are interposed between the flakes of muscovite and kaolin. A considerable number of very small flakes of black, opaque, carbonaceous matter, abundant, minute, needle-like crystals of rutile, and a very few widely scattered grains of pyrrhotite are also present. The

rutile crystals are brownish in color and occasionally display the geniculated twinning that is characteristic of this species.

The foliation of the slate explains the lack of symmetry in the expansion of columns of this rock during deformation.

The *Copper* used in these experiments was taken from a rod 1 inch in diameter, representing a good commercial grade of this metal. Prior to being turned into columns for the experiments, the pieces cut from the rod were annealed by being heated to bright redness in the coal fire of a forge, being then allowed to cool down gradually.

The *Lead* employed in the experiments was "assay lead" which, in order to free it from all air bubbles, was melted down and cast in a heated iron mold, which was then allowed to cool slowly.

METHODS EMPLOYED

Several long round bars of nickel steel $2\frac{1}{2}$ inches in diameter, all of identical composition and from the same heat, and all having been submitted to identical treatment in their manufacture, were secured. For these the authors are indebted to the Bethlehem Steel Company, which placed them at their disposal for the purpose of the present investigation.

This steel, which is very uniform in character, possesses a high tensile strength, as well as a high elastic limit, and has the following chemical composition:

Carbon	.30 per cent
Manganese	.74 per cent
Silicon	.162 per cent
Phosphorus	.035 per cent
Sulphur	.038 per cent
Nickel	4.740 per cent

The bars were sawed into lengths of about $3\frac{1}{4}$ inches. These were then bored and turned into tubes, the longitudinal sections of which, with the final dimensions, are shown in the upper half of Fig. 1. Two sets of these tubes were prepared, differing only in the thickness of the wall of the central portion of the tube. In the first set this has a thickness of 0.33 centimeter, while in the second

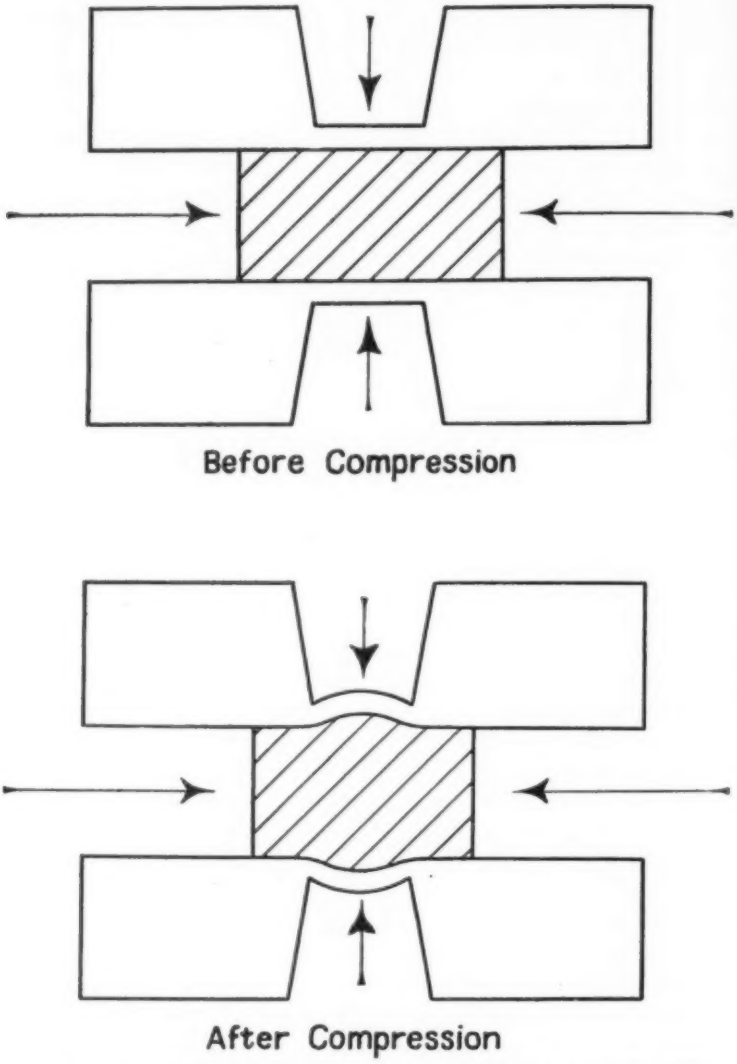

FIG. 1.—Longitudinal section through steel cylinder with wall 0.33 cm. thick, and inclosing one of the rock columns (natural scale).

set the thickness is 0.25 centimeter. The interior diameter of the tube in both sets is of such a size that it will just receive a column of rock 2 centimeters in diameter. The inner surface of the tube in every case was not only perfectly smooth, but highly polished. The angle of the bevel, by which the thickness of the wall is reduced at the middle of the tube, was adopted after a long series of preliminary experiments, which proved it to be that which was demanded by the conditions to be secured. Pistons fitting accurately into either end of these tubes were then made of chromium tungsten steel, suitably tempered by being heated, quenched in oil, and then ground to the exact dimensions required.

Large blocks of each of the rocks having been secured, rough columns of them were bored out by means of a hollow-bit diamond drill, care being taken in the case of each rock to have all the columns bored out of the rock in the same direction, that is, parallel to one another, so that any possible variations due to rift, grain, or incipient foliation were avoided. These rough columns were then reduced to the exact size required, by being ground down in a lathe by means of revolving carborundum wheels of different degrees of fineness, and were finally highly polished. When completed the columns were of such a size that they would just pass into the steel tubes at the ordinary temperature, the tube inclosing the column with an absolutely perfect mechanical fit. The column was in each case 4 centimeters long and 2 centimeters in diameter. While the column was thus fitted accurately into the tube, it could, by the exertion of a certain amount of pressure, be moved up and down within the tube. The column of rock, when inserted into the tube, was so placed that its center was exactly in the center of the thinner portion of the tube, as shown in the diagram, the extremities of the column being in this way supported by the walls of the thicker portion of the tube at either end.

The pressure to which the rock was submitted was obtained by a Wicksteed testing machine set up in the Testing Laboratory of the Macdonald Engineering Building of McGill University. This machine has a capacity of 100 tons and, when loaded to its capacity, is sensitive to a load of 4 pounds. Unfortunately, being graduated to read only in tons and pounds, it was necessary to obtain the data

of the research in these units. In presenting the final results, however, the data for the conversion of these into a unit more generally employed in physical investigations are given.

The extensometer employed for the purpose of measuring the expansion of the tube under pressure was a simplified form of the type designed by Professor Coker and described in the *Proceedings of the Royal Society of Edinburgh*, XXV (1904–5). It was affixed to the opposite points of the steel tube on the plane of maximum deformation and showed the expansion, multiplied by two, by means of a fine line moving over a graduated scale, which was read by a telescope placed at a distance of several feet.

In a number of experiments two extensometers were employed, which were applied to the tube in the plane of maximum deformation, but in directions at right angles to one another. In this way it was ascertained that the bulge which the steel tube displayed under pressure was nearly symmetrical, but in order that any error which might arise from a single measurement might be eliminated, in almost all cases the two extensometers employed were affixed to the tube at right angles to one another, and the mean of the two readings was secured. By means of this form of extensometer and by reading with a telescope, it was possible to measure an increase on the diameter of the tube amounting to only 0.0005 inch. The steel tube inclosing the rock column, with the extensometers in position, the whole set up in the press ready for the application of pressure, is shown in Fig. 2.

The method adopted for measuring the internal friction developed in the rock by deformation was as follows:

A column of rock, Carrara marble, first was taken, having the dimensions already referred to. This was inclosed in a tube of nickel steel, as above described; the tube had a wall thickness of 0.25 centimeter at its thinner portion. As will be seen from Fig. 1, the middle portion of the marble column is inclosed by the thinner portion of the tube, while the ends of the column are held by the thicker portion of the tube wall. In this way the rock is prevented from flowing up between the tube and the pistons and thus from escaping from the tube. With a tube of this shape and these dimensions, the movement of the rock under pressure is confined

to the middle portion of the column, which is surrounded by the thinner portion of the tube. The pistons being inserted and the whole properly set up in the testing machine, the pressure was

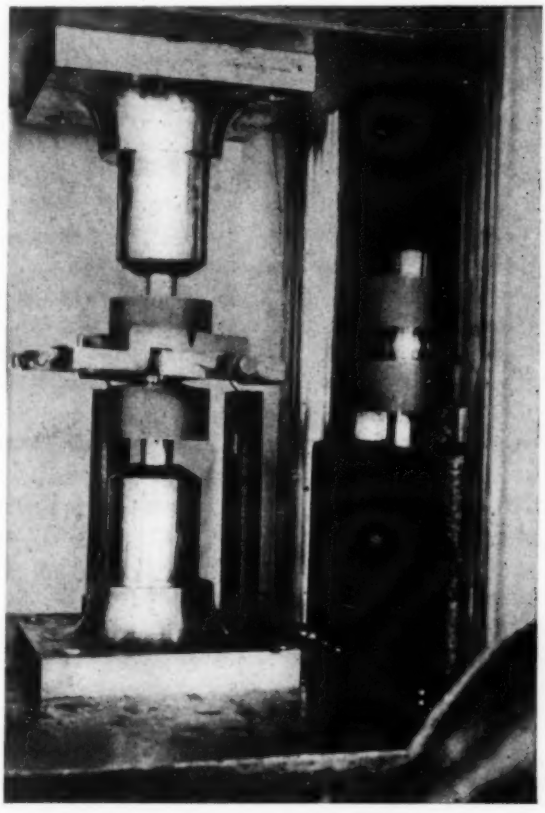

FIG. 2.—Steel cylinder, inclosing a rock column and with the two extensometers in position, set up in the Wicksteed press. To the right a bulged cylinder is shown as it appears at the close of an experiment.

applied in successive increments of 1,000 pounds. The extensometer showed no yielding of the inclosed rock until a load of about 12,000 pounds had been reached, when a very slight distension of

the tube was indicated. Up to this point, the marble, being an elastic body, was undergoing cubic compression, the pressure exerted by the machine and the resistance exerted by the steel collar being equal. The slight distension of the steel tube at a load of 12,000 pounds is due to the elastic deformation of the marble. After each additional increase of 1,000 pounds to the load, extensometer readings were taken every 30 seconds until four successive readings were identical, that is to say, until no movement that could be registered on the scale took place during a period of 2 minutes. The pressure was then increased by another 1,000 pounds and a similar series of readings were taken. This was continued until the bulging steel tube showed signs of rupture or was actually ruptured by the movement of the inclosed rock. The time which elapsed between the first application of pressure and the final rupture of the tube, that is to say, the duration of the experiment, differed somewhat in the different experiments, but may be said to be about four hours.

During the time which elapses from the point when the elastic limit of the rock is exceeded to that at which the tube fails, the inclosed rock is undergoing deformation with extreme slowness and by internal movements of one kind or another, which give rise to what may be termed a plastic flow.

At the commencement of the experiment the column of marble had the form and dimensions represented in the upper half of Fig. 1. When at the conclusion of the experiment the test piece was placed in a lathe and the steel collar was turned off, the specimen of marble was set free. It was still intact, unbroken, and, when tested in compression, was found to be very nearly as strong as a piece of the original marble of the same shape and size. It now had the form represented in the lower half of Fig. 1.

A photograph of a column of rock, before and after deformation, the rock, however, in this particular case being steatite, is shown in Fig. 3.

The pressure which was applied to the marble column effected two results. It overcame the pressure (or resistance) exerted upon the sides of the column by the inclosing tube of steel, and it overcame the internal friction developed within the rock during its

change of shape. If it were possible, therefore, to ascertain the amount of the pressure (or lateral resistance) exerted by the inclosing tube, it would be possible by subtracting this from the total load employed to determine the load which was required to overcome the internal friction of the rock under the conditions of the experiment.

In order to determine the amount of pressure required to effect the progressive deformation of the tube, i.e., the amount of pressure exerted by the tube on the inclosed rock during the successive stages of deformation, a series of steel tubes, identical in every respect with those employed in the experiment just described, were taken and were deformed in a precisely similar manner, except that these tubes were filled with soft tallow, instead of being occupied by a column of marble. This material was selected as being one which moves with the development of an amount of internal friction which is so small that it was negligible in the present case. In carrying out the experiment with tallow, we found it necessary to slightly alter the shape of the steel pistons, the ends inserted in the steel tube being turned so as to present a somewhat concave face, as shown in Fig. 4, the outer margins having a thin feather edge. When pressure is brought to bear upon these pistons, this thin edge expands slightly, thus pressing against the walls of the tube and preventing the tallow from escaping between the piston and the wall. It was found that in this way the deformation of the tube could be readily effected.

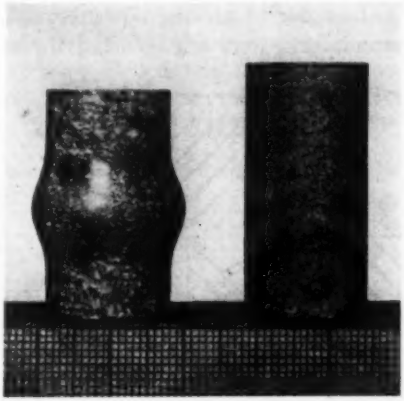

FIG. 3.—Photograph of columns of steatite before and after deformation. The smaller divisions of the scale below are millimeters.

The objection might be put forward that, while undoubtedly the tallow possesses at ordinary atmospheric pressure an internal friction which is quite negligible, this material under the pressure to which it must be subjected in order to deform the steel tube might develop an amount of internal friction and a rigidity which would be by no means negligible.

In order to ascertain whether such was the case, companion experiments were made, using the same pistons, but employing

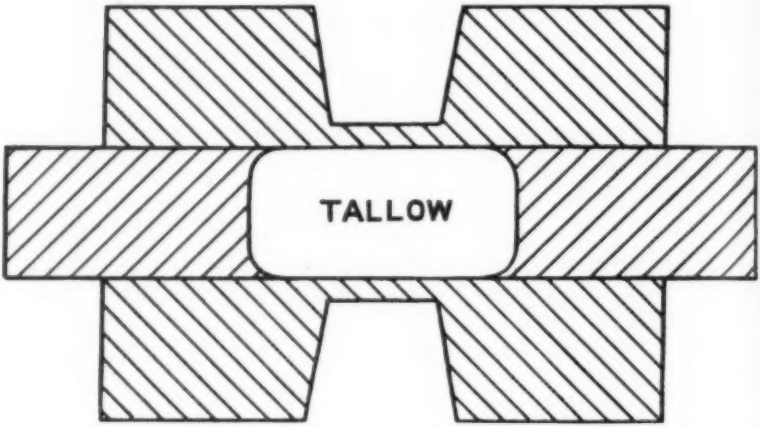

FIG. 4.—Longitudinal section through steel cylinder, showing the type of piston used when deforming the steel with tallow.

water in one case and oil in another, instead of tallow. It was found that the deformation of the tube could be effected by either of these materials, although, when water was employed, it was necessary to raise the pressure rapidly at first to cause the feather edges of the pistons to expand and make the joint tight, thus preventing the water from escaping. This series of comparative experiments was carried out with loads up to 19,000 pounds, at which pressure the tubes failed, and it was found that under these pressures the three substances mentioned—water, oil and soft tallow—showed no difference in viscosity which could be detected. The tallow, of course, undoubtedly possesses a somewhat greater inter-

nal friction than the water, but at the range of pressure to which it was submitted in the present investigation this difference is not noticeable and may therefore be neglected. The tallow, however, being more convenient for purposes of experiment, was employed in a further series of comparative experiments.

There was one other possible source of error, namely, the friction between the walls of the tube and the thin feather edge of the hollow-faced piston used in the experiments with the tallow. In the experiments with a column of rock a flat-faced piston was of course employed, and this source of friction was thus eliminated. In order to ascertain the amount of this friction in the case of the tallow, another steel tube was constructed, identical in all respects with those used in this investigation. One end of it, however, was closed so that it would be necessary to employ only a single piston, and through the closed end a small copper tube was inserted, which led to a powerful pump provided with an accurate pressure gage. The whole apparatus having been filled with water supplied by the pump, the steel tube with its cup-shaped piston was placed in a 75-ton Emery testing machine, and the piston slowly forced into the fluid, the pressure required to do this being noted at every stage on the testing machine and also on the gage fitted to the pump. In this way the pressure necessary to force the piston forward was measured at each additional increment of load applied to the piston by the Emery machine. As a result of a series of trials, it was ascertained that the friction on the feather edges of the piston amounted on an average to only 290 pounds, so that, in view of the very heavy pressure employed in this investigation, the error thus introduced is so small that it may be neglected.

It having been ascertained that soft tallow was a material which for the purposes of this investigation might be considered to move without the development of internal friction, a series of experiments were made with steel tubes identical in character and dimensions with those employed to inclose the marble, but soft tallow was substituted for marble. The two series of experiments were carried out in exactly the same manner in every detail, except that in the tubes filled with tallow the load was raised by increments of 500 pounds, instead of 1000 pounds, and the readings were taken

every 15 seconds instead of every 30 seconds till they remained constant for at least 5 consequent readings. This change was necessitated in order to standardize the conditions in the two series of experiments, since, when the tube was filled with tallow, the whole load was applied to overcome the resistance of the tube, while, when the place of the tallow was taken by marble, a portion of the load was applied to overcome the internal friction of the rock, and the movement was slower. By modifying the procedure, as above mentioned, in the case of the tubes filled with tallow an identical deformation was secured in both cases.

When columns of rock are inclosed in the steel tubes and deformation is carried out in the manner described, the impending rupture of the steel tube, which marks the conclusion of the experiment, is indicated by the appearance of a series of sharply marked vertical lines on the bulged wall of steel which inclosed the deformed rock. If the experiment is continued, the tube splits along one of these vertical lines, and the inclosed rock becomes visible, and, if the pressure is still maintained, the resistance along the line of rupture being removed, the rock along this line crumbles and is forced out of the fissure in the form of a powder.

In the case of the experiments in which tallow was employed in place of a column of rock, the completion of the test is marked by the development of a vertical fissure in the thin portion of the steel tube in the usual manner. So soon as this appears, however, and usually before the load can be taken off the testing machine, a fragment of the thin steel wall, bounded on one side by the fissure in question and at the top and bottom by the thicker portion of the steel tube, opens out like a door on its hinges and is instantly torn off and with a loud report is shot across the room with great violence. It therefore was necessary in the case of these experiments that the observer should always be protected from these projectiles, the importance of this protection being emphasized in the case of one of the experiments by the fact that the piece of steel struck and split in two the piece of hard wood, a quarter of an inch thick, which protected the observer's head.

In order to make quite sure that the form and outline of the bulge assumed by the tube in the case of the experiments with the

different rocks was the same, a special series of experiments to decide this question was made, employing copper, lead, marble, Belgian black, and granite. In each instance the experiment was carried to the point where the bulge or expansion of the diameter amounted to 0.030. The cylinder was then removed, and by using an electric arc light in a dark room a sharp shadow of the outline of the bulged cylinder was cast upon sensitive paper, removed at such a distance that the photograph enlarged the outline of the cylinder approximately 18 times. The cylinder was then placed in the Wicksteed machine, and the bulge increased to 0.110, and a similar photograph taken. By a comparison of the photographs it was found that the outline of the deformed wall was essentially identical in all cases.

As has been mentioned, from two to five experiments were made in the case of each rock when inclosed in a 0.25-centimeter tube and the same number with each rock inclosed in a tube having a wall thickness of 0.33 centimeter. The mean of the closely concordant results was then worked out in each case, and the figures obtained are presented in Tables I and II. These represent the data yielded by the experimental work.

The necessary data having been thus secured, a curve was plotted presenting these graphically in the case of each experiment. In these curves the exact amount of the load required to produce any required bulge or distension of the tube is shown from the point when the first movement can be detected until the final rupture of the tube takes place. The curves for the several experiments with Carrara marble inclosed in the steel tubes with a 0.25-centimeter wall are shown in Fig. 5 (p. 620). A curve representing the mean of the results obtained in the several experiments is also given. In Fig. 6 (p. 621) this curve of the mean of the results obtained from the marble inclosed in a 0.25-centimeter tube is reproduced, and below it is the mean of the curves obtained from tallow when inclosed in a 0.25-centimeter steel tube.

Since the tallow, as has been shown, offers itself no measurable resistance to deformation under the conditions of the experiment, the curve in the tallow experiments shows merely the resistance offered to deformation by the steel tube itself.

TABLE I

AMOUNT OF DEFORMATION, IN INCHES, OF THE SEVERAL ROCKS WHEN INCLOSED IN THE STEEL CYLINDERS HAVING A WALL THICKNESS OF 0.25 CENTIMETER

LOAD IN POUNDS*	TALLOW	LEAD	COPPER	ROCKS EMPLOYED								
				Steatite, Virginia, U.S.A.	Alabaster, Castelino, Italy	Sandstone, Cleveland, Ohio, U.S.A.	White Marble, Carrara, Italy	Dolomite, Cockeysville, Maryland, U.S.A.	Black Belgian Marble ("Noir fin")	Slate, New Rockland, Quebec, Canada	Olivine Diabase, Sudbury, Ontario, Canada	Granite, Baveno, Italy
2,000	0.0002	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
3,000	.0005	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4,000	.0008	.....	.....	.....	0.0003	.....	.....	.....	.....	.....	.....	.....
5,000	.0013	0.0004	.....	.....	.0003	.....	.....	.....	.....	.....	.....	.....
6,000	.0018	.0010	.....	.....	.0003	.....	.....	.....	.....	.....	.....	.....
7,000	.0025	.0015	.....	0.0003	.0003	.....	.....	.....	.....	.....	.....	.....
8,000	.0032	.0020	0.0003	.0004	.0003	.....	.....	.....	.....	.....	.....	.....
9,000	.0062	.0038	.0005	.0005	.0003	.....	.....	.....	.....	.....	.....	.....
10,000	.0130	.0075	.0010	.0006	.0003	.....	0.0003	.....	.....	.....	.....	.....
11,000	.0216	.0139	.0018	.0006	.0008	.....	.0005	.....	.....	.....	.....	.....
12,000	.0323	.0220	.0023	.0008	.0009	.....	.0006	.....	.....	.....	.....	.....
13,000	.0483	.0330	.0038	.0009	.0009	.....	.0006	.....	.....	.....	.....	.....
14,000	.0748	.0550	.0050	.0009	.0010	.....	.0008	.....	.....	.....	.....	.....
15,000	0.1097	.0843	.0073	.0013	.0013	.....	.0009	.....	.....	.....	.....	.....
16,000	.....	0.1133	.0098	.0013	.0013	0.0003	.0009	.....	.....	.....	.....	.....
17,000	.....	.....	.0120	.0016	.0014	.0005	.0016	.....	.....	.....	.....	.....
18,000	.....	.....	.0148	.0021	.0016	.0005	.0018	.....	.....	.....	.....	.....
19,000	.....	.....	.0175	.0026	.0021	.0005	.0018	.....	.....	.....	.....	.....
20,000	.....	.....	.0203	.0043	.0028	.0008	.0021	.....	.....	.....	.....	.....
21,000	.....	.....	.0233	.0068	.0031	.0008	.0021	.....	.....	.....	.....	.....
22,000	.....	.....	.0260	.0103	.0036	.0010	.0023	.....	.....	.....	.....	.....

23,000	.....	.....	.0295	.0145	.0045	.0010	.0028	.....	.....	.....	.....	.....
24,000	.....	.....	.0328	.0199	.0063	.0015	.0030	.....	.....	.....	.....	.....
25,000	.....	.....	.0365	.0258	.0080	.0023	.0035	.....	.....	.....	.....	.....
26,000	.....	.....	.0403	.0323	.0098	.0030	.0043	.....	.....	.....	0.0003	.....
27,000	.....	.....	.0445	.0386	.0126	.0040	.0051	.....	.....	.....	.0003	.....
28,000	.....	.....	.0488	.0462	.0151	.0065	.0068	.....	.....	.....	.0004	.....
29,000	.....	.....	.0535	.0532	.0184	.0083	.0078	0.0005	.....	.....	.0004	.....
30,000	.....	.....	.0583	.0608	.0218	.0125	.0085	.0009	0.0005	.....	.0004	.....
31,000	.....	.....	.0640	.0694	.0258	.0155	.0110	.0011	.0010	.....	.0006	.....
32,000	.....	.....	.0708	.0779	.0318	.0198	.0126	.0011	.0010	.....	.0006	0.0004
33,000	.....	.....	.0768	.0872	.0353	.0238	.0139	.0011	.0010	.....	.0009	.0004
34,000	.....	.....	.0840	.0972	.0419	.0283	.0169	.0013	.0010	.....	.0009	.0004
35,000	.....	.....	.0923	.1072	.0473	.0330	.0181	.0016	.0010	.....	.0009	.0004
36,000	.....	.....	.0995	.1184	.0556	.0368	.0208	.0031	.0013	.....	.0009	.0004
37,000	.....	.....	0.1093	.1300	.0868†	.0423	.0234	.0036	.0013	.....	.0014	.0004
38,000	.....	.....	.....	0.1512	.0893	.0483	.0268	.0040	.0018	.....	.0014	.0004
39,000	.....	.....	.....	.....	.0935	.0535	.0296	.0040	.0020	.....	.0014	.0004
40,000	.....	.....	.....	.....	.0990	.0593	.0326	.0045	.0020	0.0004	.0014	.0004
41,000	.....	.....	.....	.....	.1048†	.0650	.0354	.0048	.0020	.0008	.0014	.0004
42,000	.....	.....	.....	.....	.1123	.0738	.0386	.0053	.0023	.0008	.0018	.0004
43,000	.....	.....	.....	.....	.1231	.0800	.0416	.0060	.0023	.0009	.0018	.0008
44,000	.....	.....	.....	.....	.1324	.0880	.0464	.0075	.0025	.0009	.0018	.0008
45,000	.....	.....	.....	.....	.1458	.0958	.0511	.0091	.0030	.0009	.0020	.0010
46,000	.....	.....	.....	.....	0.1559	.1050	.0560	.0108	.0033	.0010	.0020	.0010
47,000	.....	.....	.....	.....	.....	.1145	.0613	.0129	.0038	.0011	.0025	.0010
48,000	.....	.....	.....	.....	.....	.1235	.0658	.0153	.0040	.0011	.0025	.0010
49,000	.....	.....	.....	.....	.....	.1323	.0716	.0181	.0053	.0013	.0028	.0010
50,000	.....	.....	.....	.....	.....	.1398	.0768	.0224	.0063	.0013	.0031	.0010
51,000	.....	.....	.....	.....	.....	.1493	.0819	.0255	.0085	.0015	.0031	.0011
52,000	.....	.....	.....	.....	.....	0.1580	.0879	.0301	.0108	.0018	.0035	.0013
53,000	.....	.....	.....	.....	.....	.....	.0936	.0351	.0135	.0020	.0040	.0014
54,000	.....	.....	.....	.....	.....	.....	.0989	.0406	.0165	.0021	.0043	.0015
55,000	.....	.....	.....	.....	.....	.....	0.1063	0.0471	0.0210	0.0022	0.0043	0.0016

* Each 1,000 pounds of load as given in Column I = 2,052.7 pounds per square inch = 139.64 atmospheres.

† Between the daggers in the column pertaining to Alabaster the results are irregular because in one of the experiments there was an impact delivered to the specimen, as explained in the discussion of Fig. 12.

TABLE I—*Continued*

Load in Pounds*	Tallow	Lead	Copper	Rocks Employed								
				Steatite, Virginia, U.S.A.	Alabaster, Castelino, Italy	Sandstone, Cleveland, Ohio, U.S.A.	White Marble, Carrara, Italy	Dolomite, Cockeysville, Maryland, U.S.A.	Black Belgian Marble, ("Noir fin")	Slate, New Rockland, Quebec, Canada	Olivine Diabase, Sudbury, Ontario, Canada	Granite, Baveno, Italy
56,000							0.1109	0.0546	0.0258	0.0026	0.0048	0.0016
57,000							.1155	.0604	.0313	.0085	.0051	.0018
58,000							.1219	.0671	.0360	.0091	.0056	.0021
59,000							.1282	.0754	.0413	.0103	.0070	.0023
60,000							.1349	.0818	.0485	.0108	.0078	.0023
61,000							.1405	.0895	.0543	.0119	.0084	.0024
62,000							.1459	.0968	.0613	.0150	.0089	.0026
63,000							0.1505	.1041	.0665	.0335	.0098	.0026
64,000								.1110	.0723	.0447	.0113	.0029
65,000								.1178	.0838	.0540	.0125	.0031
66,000								.1265	.0898	.0680	.0136	.0033
67,000								.1344	.0980	.0801	.0159	.0036
68,000								.1410	.1073	.0905	.0178	.0036
69,000								.1494	.1143	.0981	.0206	.0041
70,000								.1569	.1235	.1116	.0247	.0045
71,000								0.1651	.1315	.1223	.0289	.0049
72,000									.1395	.1316	.0330	.0050
73,000									.1540	.1432	.0396	.0055
74,000									0.1648	0.1521	.0475	.0060
75,000											.0554	.0069
76,000											.0650	.0076
77,000											.0744	.0089
78,000											.0839	.0121
79,000											.0939	.0290

80,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.1038	.0434
81,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.1131	.0554
82,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.1230	.0636
83,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.1321	.0708
84,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.1405	.0793
85,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.1505	.0868
86,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.0961
87,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.1000
88,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.1143
89,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.1234
90,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.1308
91,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.1418
92,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.1498
Number of experiments performed	3	2	2	4	2	2	4	2	2	2	2	2
Average duration of each experiment	0 hr. 52 min.	1 hr. 10 min.	1 hr. 32 min.	2 hr. 11 min.	2 hr. 22 min.	4 hr. 0 min.	4 hr. 0 min.	4 hr. 32 min.	4 hr. 14 min.	3 hr. 49 min.	4 hr. 56 min.	4 hr. 11 min.

*Each 1,000 pounds of load as given in Column I = 2,052.7 pounds per square inch = 139.64 atmospheres.

TABLE II

AMOUNT OF DEFORMATION, IN INCHES, OF THE SEVERAL ROCKS WHEN INCLOSED IN THE STEEL CYLINDERS HAVING A WALL THICKNESS OF 0.33 CENTIMETER

LOAD IN POUNDS*	TALLOW	LEAD	COPPER	ROCKS EMPLOYED								
				Steatite, Virginia, U.S.A.	Alabaster, Castelino, Italy	Sandstone, Cleveland, Ohio, U.S.A.	White Marble, Carrara, Italy	Dolomite, Cockeysville, Maryland, U.S.A.	Black Belgian Marble, ("Noir fin")	Slate, New Rockland, Quebec, Canada	Olivine Diabase, Sudbury, Ontario, Canada	Granite, Baveno, Italy
4,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
5,000	0.0004	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
6,000	.0005	0.0005	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
7,000	.0008	.0008	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
8,000	.0010	.0013	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
9,000	.0012	.0013	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
10,000	.0018	.0019	0.0003	.....	.....	.....	.....	.....	.....	.....	.....	.....
11,000	.0028	.0025	.0006	0.0004	.....	.....	.....	.....	.....	.....	.....	.....
12,000	.0055	.0040	.0010	.0005	.....	.....	.....	.....	.....	.....	.....	.....
13,000	.0095	.0080	.0013	.0007	0.0004	.....	.....	.....	.....	.....	.....	.....
14,000	.0153	.0116	.0017	.0009	.0006	.....	0.0005	.....	.....	.....	.....	.....
15,000	.0212	.0173	.0018	.0010	.0006	.....	.0008	.....	.....	.....	.....	.....
16,000	.0280	.0240	.0023	.0013	.0006	0.0003	.0010	.....	.....	.....	.....	.....
17,000	.0367	.0313	.0026	.0013	.0008	.0003	.0010	.....	.....	.....	.....	.....
18,000	.0475	.0419	.0033	.0017	.0008	.0005	.0010	.....	.....	.....	.....	.....
19,000	.0645	.0560	.0040	.0021	.0009	.0005	.0010	.....	.....	.....	.....	.....
20,000	.0848	0.0805	.0050	.0025	.0009	.0008	.0013	.....	.....	.....	.....	.....
21,000	0.1152	.....	.0065	.0028	.0013	.0008	.0013	.....	.....	.....	.....	.....
22,000	.....	.....	.0078	.0029	.0014	.0008	.0015	0.0003	.....	.....	.....	.....
23,000	.....	.....	.0098	.0034	.0015	.0008	.0018	.0003	.....	.....	.....	.....
24,000	.....	.....	.0117	.0038	.0019	.0008	.0020	.0003	.....	.....	.....	.....

25,000	.....	.....	.0138	.0050	.0026	.0008	.0020	.0003	.....	.....	.....	.....
26,000	.....	.....	.0155	.0071	.0029	.0010	.0020	.0003	.....	.....	.....	.....
27,000	.....	.....	.0187	.0093	.0031	.0010	.0023	.0003	.....	.....	.....	.....
28,000	.....	.....	.0212	.0116	.0038	.0010	.0023	.0004	0.0003	.....	.....	.....
29,000	.....	.....	.0238	.0146	.0043	.0010	.0028	.0006	.0003	.....	.....	.....
30,000	.....	.....	.0273	.0173	.0051	.0011	.0030	.0008	.0003	.....	.....	.....
31,000	.....	.....	.0305	.0212	.0061	.0013	.0040	.0009	.0003	.....	.....	.....
32,000	.....	.....	.0345	.0237	.0075	.0013	.0040	.0010	.0007	.....	.....	.....
33,000	.....	.....	.0387	.0265	.0089	.0018	.0050	.0011	.0007	.....	.....	.....
34,000	.....	.....	.0426	.0306	.0114	.0043	.0063	.0011	.0007	.....	.....	.....
35,000	.....	.....	.0470	.0333	.0126	.0058	.0078	.0013	.0007	.....	0.0003	
36,000	.....	.....	.0518	.0379	.0163	.0084	.0085	.0014	.0007	.....	.0003	0.0005
37,000	.....	.....	.0570	.0415	.0186	.0106	.0093	.0014	.0008	.....	.0005	.0005
38,000	.....	.....	.0630	.0456	.0209	.0141	.0108	.0015	.0009	.....	.0009	.0005
39,000	.....	.....	.0688	.0481	.0238	.0164	.0128	.0018	.0009	.....	.0009	.0005
40,000	.....	.....	.0760	.0537	.0269	.0188	.0140	.0019	.0009	.....	.0009	.0005
41,000	.....	.....	.0838	.0601	.0309	.0210	.0150	.0021	.0010	.....	.0009	.0005
42,000	.....	.....	.0915	.0658	.0348	.0243	.0170	.0021	.0012	0.0007	.0011	.0005
43,000	.....	.....	0.0987	.0714	.0370	.0273	.0185	.0024	.0013	.0007	.0011	.0005
44,000	.....	.....	.....	.0789	.0451	.0298	.0210	.0026	.0013	.0009	.0011	.0010
45,000	.....	.....	.....	.0856	.0494	.0325	.0230	.0028	.0013	.0009	.0011	.0010
46,000	.....	.....	.....	.0939	.0558	.0349	.0258	.0031	.0013	.0009	.0014	.0010
47,000	.....	.....	.....	.1023	.0615	.0389	.0270	.0040	.0015	.0009	.0014	.0010
48,000	.....	.....	.....	.1117	.0680	.0427	.0300	.0044	.0016	.0009	.0014	.0010
49,000	.....	.....	.....	.1217	.0742	.0452	.0320	.0054	.0017	.0011	.0014	.0010
50,000	.....	.....	.....	.1333	.0820	.0493	.0358	.0063	.0022	.0011	.0014	.0010
51,000	.....	.....	.....	.1428	.0922	.0535	.0373	.0068	.0025	.0013	.0017	.0010
52,000	.....	.....	.....	0.1525	.0980	.0570	.0408	.0086	.0030	.0013	.0017	.0010
53,000	.....	.....	.....	.....	.1074	.0610	.0458	.0096	.0042	.0013	.0017	.0010
54,000	.....	.....	.....	.....	.1175	.0656	.0485	.0114	.0053	.0013	.0021	.0010
55,000	.....	.....	.....	.....	.1265	.0695	.0530	.0131	.0073	.0015	.0021	.0015
56,000	.....	.....	.....	.....	.1356	.0740	.0558	.0155	.0084	.0016	.0023	.0015
57,000	.....	.....	.....	.....	.1456	.0783	.0600	.0179	.0110	.0018	.0025	.0015
58,000	.....	.....	.....	.....	0.1569	0.0830	0.0630	0.0204	0.0138	0.0019	0.0025	0.0015

* Each 1,000 pounds of load as given in Column I = 2,052.7 pounds per square inch = 139.64 atmospheres.

TABLE II—*Continued*

Load in Pounds*	Tallow	Lead	Copper	Rocks Employed								
				Steatite, Virginia, U.S.A.	Alabaster, Castelino, Italy	Sandstone, Cleveland, Ohio, U.S.A.	White Marble, Carrara, Italy	Dolomite, Cockeysville, Maryland, U.S.A.	Black Belgian Marble, ("Noir fin")	Slate, New Rockland, Quebec, Canada	Olivine Diabase, Sudbury, Ontario, Canada	Granite, Baveno, Italy
59,000	.....	.....	.....	.....	.....	0.0887	0.0658	0.0235	0.0175	0.0019	0.0028	0.0020
60,000	.....	.....	.....	.....	.....	.0952	.0690	.0256	.0204	.0020	.0030	.0021
61,000	.....	.....	.....	.....	.....	.1012	.0728	.0300	.0237	.0023	.0030	.0023
62,000	.....	.....	.....	.....	.....	.1060	.0765	.0336	.0274	.0025	.0034	.0024
63,000	.....	.....	.....	.....	.....	.1115	.0825	.0370	.0312	.0029	.0038	.0024
64,000	.....	.....	.....	.....	.....	.1168	.0865	.0410	.0339	.0030	.0040	.0026
65,000	.....	.....	.....	.....	.....	.1223	.0900	.0450	.0380	.0030	.0043	.0027
66,000	.....	.....	.....	.....	.....	.1278	.0938	.0496	.0424	.0035	.0048	.0028
67,000	.....	.....	.....	.....	.....	.1330	.1013	.0544	.0466	.0035	.0050	.0031
68,000	.....	.....	.....	.....	.....	.1378	.1055	.0588†	.0506	.0039	.0052	.0031
69,000	.....	.....	.....	.....	.....	.1445	.1103	.0646†	.0550	.0040	.0056	.0034
70,000	.....	.....	.....	.....	.....	.1498	.1155	.0681	.0585	.0041	.0056	.0035
71,000	.....	.....	.....	.....	.....	0.1553	.1205	.0719	.0649	.0046	.0066	.0036
72,000	.....	.....	.....	.....	.....	.....	.1253	.0761	.0697	.0050	.0073	.0036
73,000	.....	.....	.....	.....	.....	.....	.1270	.0810	.0760	.0050	.0083	.0037
74,000	.....	.....	.....	.....	.....	.....	.1353	.0858	.0806	.0056	.0090	.0039
75,000	.....	.....	.....	.....	.....	.....	.1400	.0909	.0844	.0060	.0096	.0041
76,000	.....	.....	.....	.....	.....	.....	.1441	.0964	.0900	.0135	.0105	.0043
77,000	.....	.....	.....	.....	.....	.....	.1488	.1025	.0960	.0226	.0115	.0048
78,000	.....	.....	.....	.....	.....	.....	.1540	.1080	.1017	.0273	.0129	.0052
79,000	.....	.....	.....	.....	.....	.....	.1583	.1131	.1059	.0300	.0139	.0055
80,000	.....	.....	.....	.....	.....	.....	.1635	.1174	.1139	.0356	.0149	.0058
81,000	.....	.....	.....	.....	.....	.....	.1685	.1229	.1194	.0525	.0176	.0065
82,000	.....	.....	.....	.....	.....	.....	0.1738	.1290	.1247	.0609	.0199	.0072

83,000	.....	.....	.....	.....	.....	.....	.....	.1365	.1298	.0675	.0223	.0079
84,000	.....	.....	.....	.....	.....	.....	.....	.1428	.1373	.0748	.0255	.0087
85,000	.....	.....	.....	.....	.....	.....	.....	.1476	.1438	.0814	.0288	.0098
86,000	.....	.....	.....	.....	.....	.....	.....	0.1543	0.1495	.0894	.0351	.0117
87,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.0970	.0420	.0136
88,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.1053	.0484	.0159
89,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.1120	.0575	.0183
90,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.1194	.0609	.0213
91,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.1263	.0678	.0249
92,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.1320	.0739	.0308
93,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.1407	.0808	.0341
94,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.0864	.0402
95,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.0928	.0444
96,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.0987	.0493
97,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.1067	.0548
98,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.1133	0607
99,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.1198	.0651
100,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.1277	.0718
101,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.1349	.0793
102,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.0859
103,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.0896
104,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.0978
105,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.1048
106,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.1106
107,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.1170
108,000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.1231
Number of experiments performed	2	2	3	5	2	2	3	3	3	2	2	4
Average duration of each experiment	1 hr. 4 min.	1 hr. 20 min.	2 hr. 3 min.	3 hr. 1 min.	3 hr. 32 min.	5 hr. 36 min.	6 hr. 0 min.	5 hr. 26 min.	4 hr. 39 min.	4 hr. 23 min.	5 hr. 14 min.	5 hr. 9 min.

*Each 1,000 pounds of load as given in Column I = 2,052.7 pounds per square inch = 139.64 atmospheres.

†Between the daggers in the column pertaining to Dolomite the results are irregular because in one of the experiments the load was removed and when later restored a slight impact was delivered to the deforming rock column.

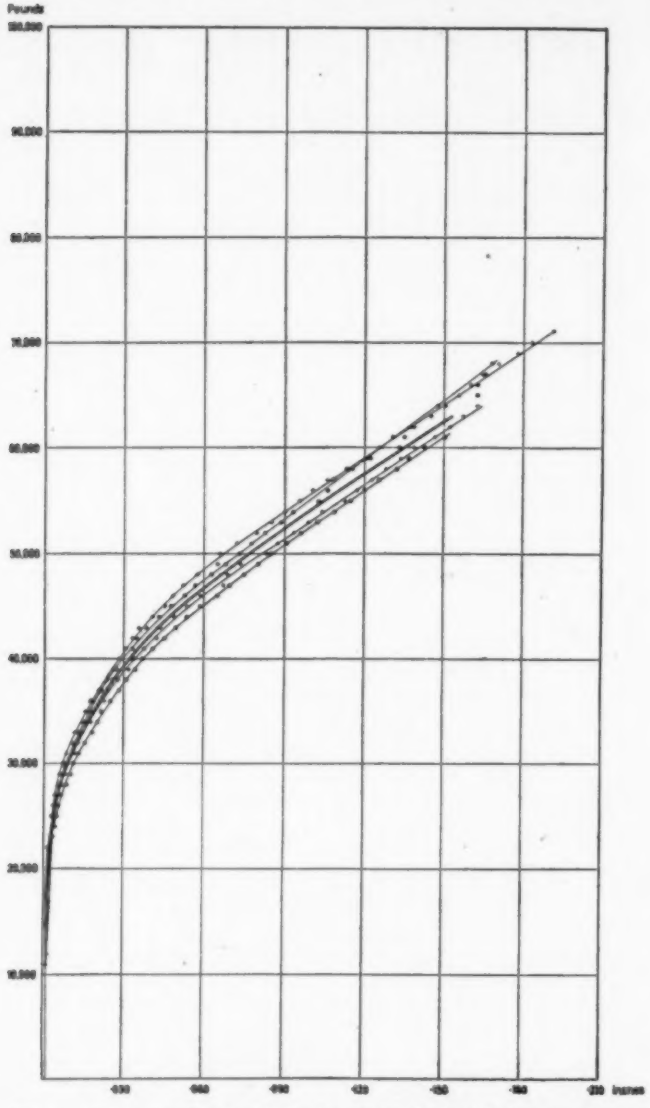

FIG. 5.—Curves showing graphically the results obtained in four experiments on the deformation of Carrara marble when it is inclosed in a steel cylinder with wall 0.25 cm. thick—also the mean of these curves (in heavy line).

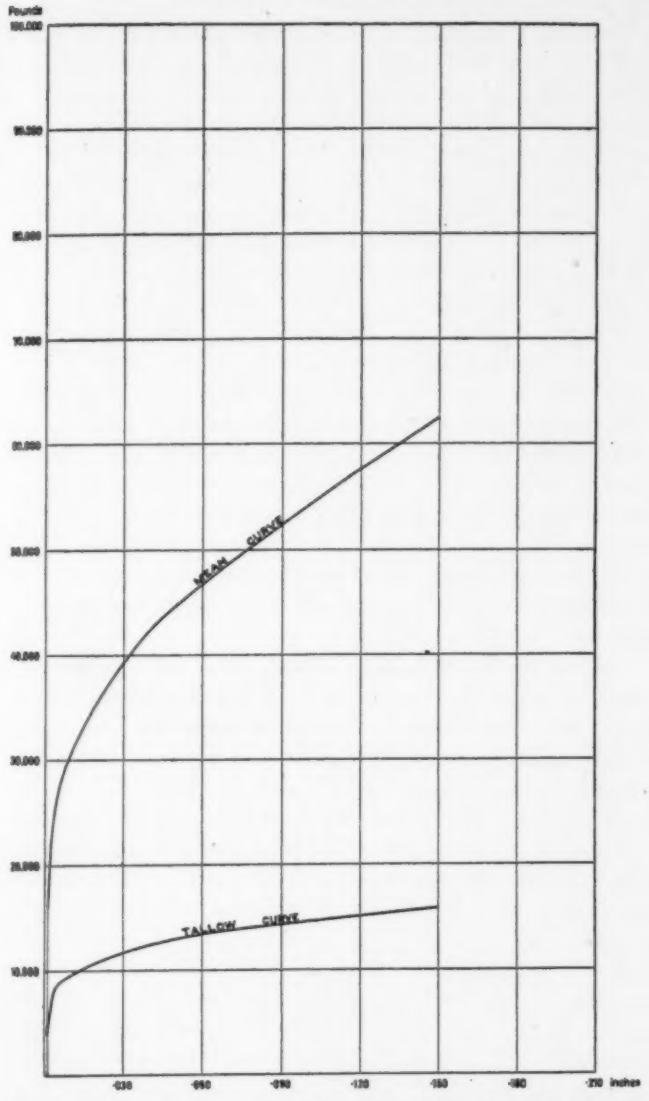

FIG. 6.—The mean of the curves obtained in the deformation of Carrara marble (see Fig. 5) when it is inclosed in a steel cylinder with wall 0.25 cm. thick—with the curve obtained when a steel tube of identical dimensions is deformed when filled with tallow.

Such being the case, with the information thus secured it is possible to separate the two components of the load, namely, that necessary to overcome the resistance offered by the tube and that required to effect the deformation of the marble. If at a series of points the load required to produce a certain distension or bulge in the steel tube when filled with the tallow is subtracted from the load required to produce the same bulge in the case of the tube containing the marble, values are obtained which represent that portion of the load which is expended in affecting the deformation of the marble. This may be termed the *true curve*, and that obtained for a standard column of Carrara marble deformed in a standard steel tube having a wall thickness of 0.25 centimeter is shown in Fig. 7. In the same manner the *true curve* for each of the other rocks may be plotted from the data presented in Tables I and II. It will be seen that, in the case of Carrara marble, this curve starting from a distension of 0.001, which may be considered to be due to elastic deformation, and which is produced by a load of 12,000 pounds, shows a rapid deflection to a point representing a distension of 0.052 which is produced by a load of 33,000 pounds, after which it develops into what is practically a straight line until the tube ruptures.

This shows that after the elastic limit of the marble has been passed, at about 12,000 pounds, and the marble commences to deform, the load which is required to start this movement and produce a unit of diametral expansion is relatively great. As the movement progresses the additional increment of load required to produce a unit of diametral expansion grows progressively less till a bulge of 0.052 is reached, after which there is a definite and constant ratio between the increase of load and the expansion which it produces. This ratio is 0.0065 for each increase of 1,000 pounds in load.

It will be noted that in the case of the slate, just after the rock began to deform, the curve shows a sudden break or sag which is repeated at a second point before the regular movement, indicated by the nearly straight line, is developed. This is due to the fact, above mentioned, that the slate, being a foliated and not a granular rock, is not isotropic in its response to pressure. It consists of little

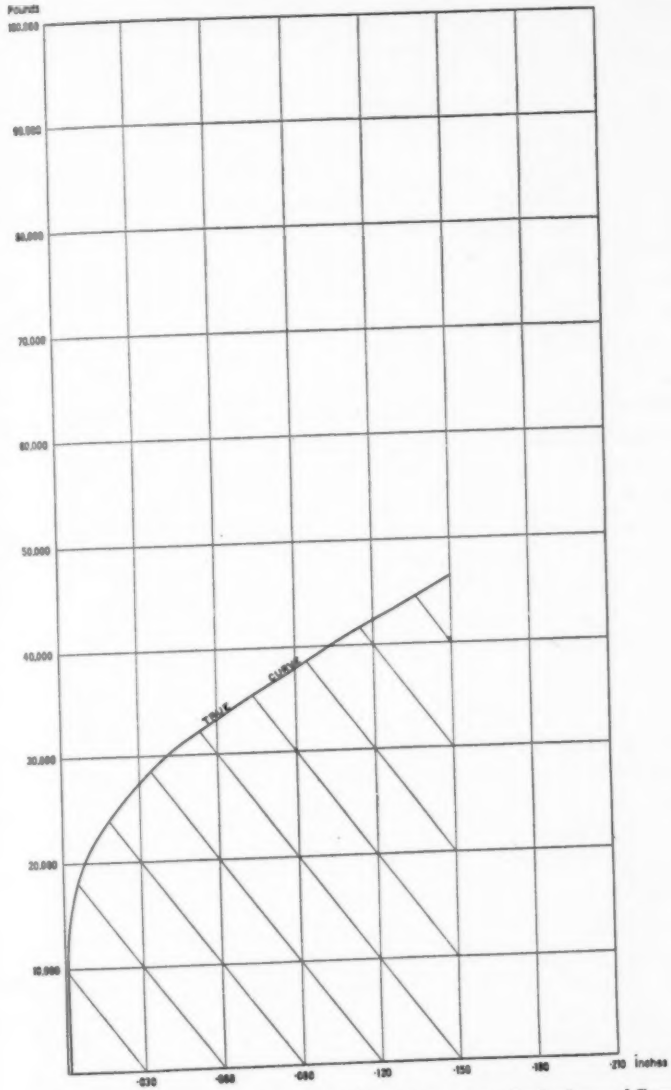

FIG. 7.—True curve obtained by the deformation of a standard column of Carrara marble in steel cylinder with wall 0.25 cm. thick. The area designated by oblique lines represents the work done in effecting the deformation of the marble to a bulge of 0.150 inch.

plates of kaolin and muscovite lying parallel to one another and at right angles to the direction in which the pressure is exerted. The breaking down of the foliated structure of the rock is indicated on the curves by the irregularities to which reference has been made.

It will also be seen that in the case of granite, when the lateral resistance is relatively low (e.g., when the rock is inclosed in the steel tube having a 0.25-centimeter wall), there is at the same point a sag, though much less marked, due to the fact that the lateral resistance offered by the tube is not quite sufficient to develop a uniform movement in this the strongest of all the rocks employed in the investigation.

Attention must be drawn to the manner in which deformation goes forward in a column of rock when deformed under the conditions of the experiment. As may be seen, if the tube and the inclosed rock are sawed in two vertically, the column of rock begins to move or flow at the middle, the motion taking place first along the well-known shearing cones, having an angle of approximately 45° (usually somewhat greater), seen when a column or cube of the rock is crushed between the faces of a testing machine in the ordinary determinations of the strength of rock for building purposes. Thus, as the movement progresses, there develops within the column two obtuse cones, having as their bases the faces of the advancing pistons and consisting of portions of the rock which show no evidences whatsoever of deformation, but which are, under the conditions of the experiment, subjected only to cubic compression. As the experiment progresses, these cones (see *A* and *B* in Fig. 8) advance into the deforming rock, additional amounts of the rock shearing off the surfaces of the cones and thus coming to participate in the movements which are going forward. Owing to the fact, therefore, that the quantity of flowing rock is continually increasing in an unknown ratio, it is impossible from the data mentioned above to determine whether the definite increase in the ratio of load to deformation is due to an increase of internal friction developed with increase of pressure, or to the increased amount of material which is being moved.

The answer to this question is obtained from another series of experiments which exactly duplicated those with the columns of

Carrara marble, described above, except that the lateral resistance to movement was increased by increasing the thickness of the walls of the steel tube inclosing the marble from a thickness of 0.25 centimeter to 0.33 centimeter. In these the amount of material moved is identical with that in the series of experiments just described, while the internal friction is increased by the increased thickness of the steel tube.

A series of additional experiments were also made to determine the resistance offered by such tubes when filled with soft tallow.

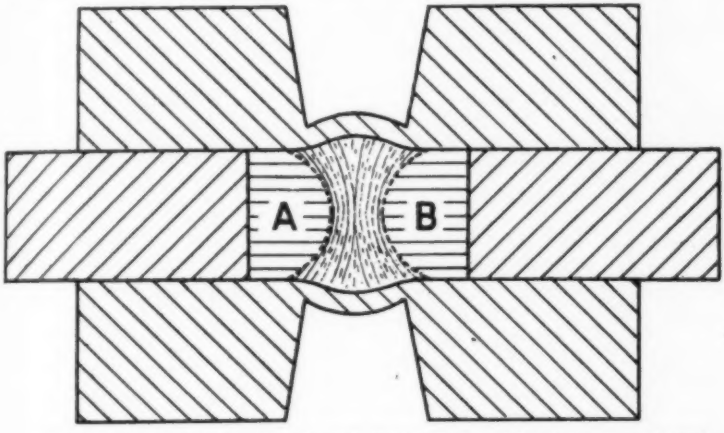

FIG. 8.—Longitudinal section through steel cylinder with pistons inserted and inclosing a deformed column of rock—showing the obtuse shearing cones which advance into the deforming rock.

In this way another series of curves were obtained for each material and another "true curve" for the deformation of a standard column of Carrara marble under conditions identical with those of the former experiments, except that the resistance to deformation offered by the steel tube was much greater. The "true curve" for the deformation of the marble in a steel tube having walls 0.33 centimeter thick is shown in Fig. 10.

An inspection of this curve will show that while, as before, starting from the limit of elastic expansion the rising load at first induces a relatively small amount of movement in the rock, the

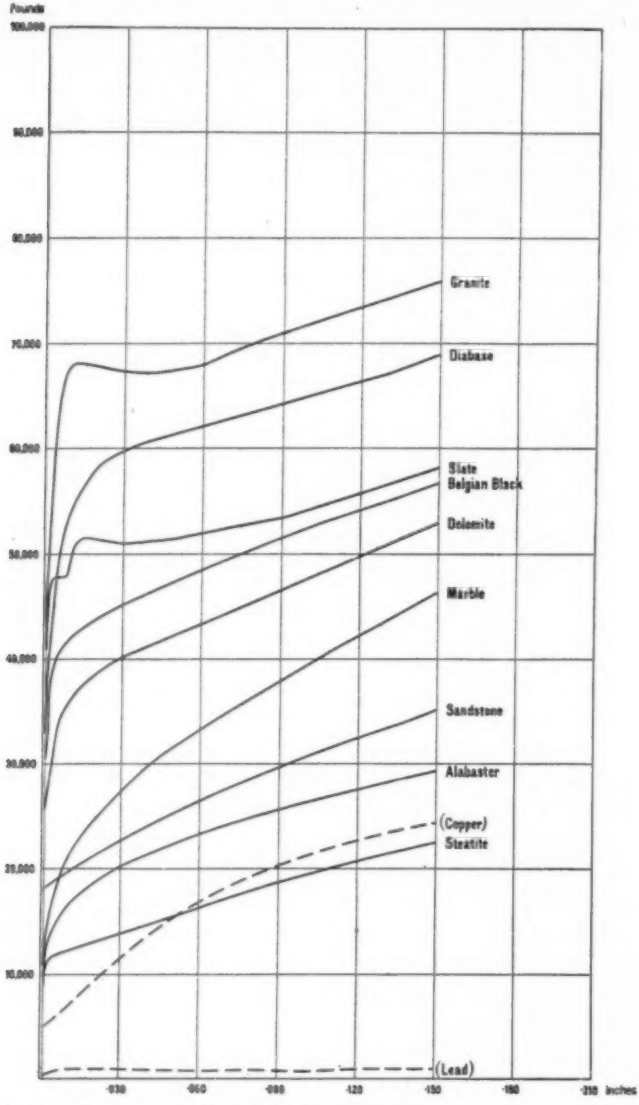

FIG. 9.—True curves obtained by the deformation of the several rocks when inclosed in the steel cylinders with wall 0.25 cm. thick.

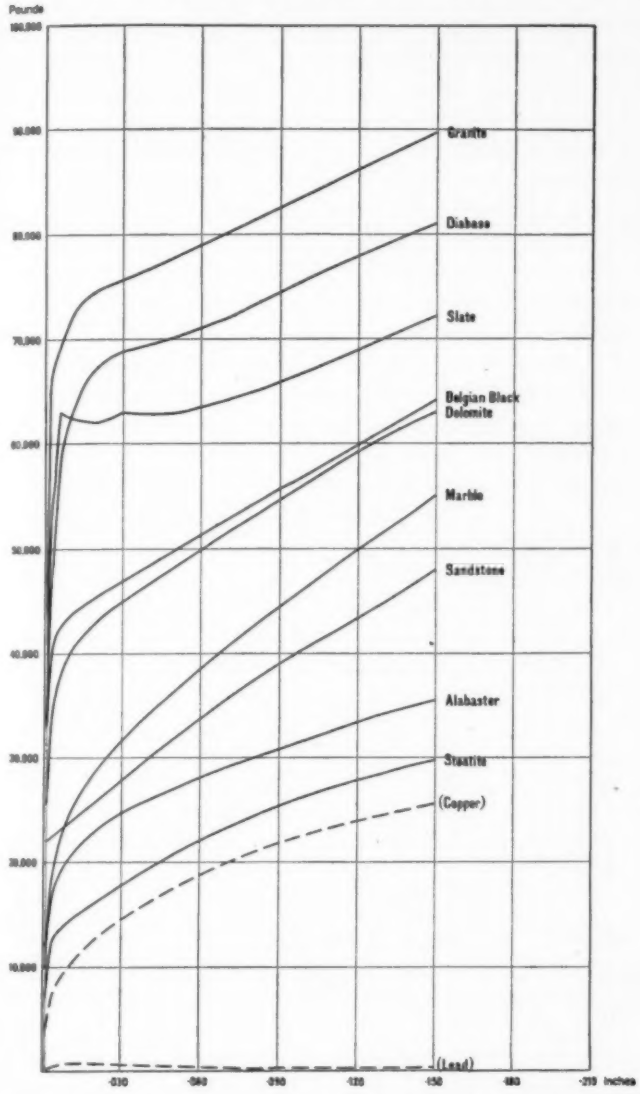

FIG. 10.—True curves obtained by the deformation of the several rocks when inclosed in the steel cylinders with wall 0.33 cm. thick.

ratio of the amount of this movement to increment of loads increases rather rapidly, and, after deformation amounting to about 0.06 has been brought about—which requires a load of 38,750 pounds—the ratio of increase of load to amount of deformation of the column becomes constant, as when the marble is deformed in the tubes with thinner walls. It will be seen, however, that for the experiments in the thicker-walled tube this ratio of increase is much less than when the wall was thinner, i.e., 0.25 centimeter being 0.0051 diametrical increase for each increase of 1,000 pounds in the load, instead of .0065, as in the first series of experiments.

This demonstrates that the moving rock possesses internal friction and that with the increase of the lateral resistance the amount or coefficient of friction rapidly increases, and at a constant ratio.

The investigation was then extended to the other rocks of the series enumerated on pp. 598 and 599. The conditions and method of conducting the experiments were in every case identical with those just described with Carrara marble. Two sets of standard steel tubes, having wall thicknesses of 0.25 centimeter and 0.33 centimeter, respectively, were employed, and the true curves were plotted representing the mean of a series of experiments in each case (see Figs. 9 and 10).

"WORK DONE" IN THE DEFORMATION OF ROCKS

If Px be the load to which the specimen is subjected and Py be the resistance to movement offered by the inclosing walls of the steel cylinder, the data were first examined to ascertain whether the formula

$$Px-Py=\text{a constant}$$

represents the movement, and it was found that this was not the case. They were then studied to see whether each rock possessed a constant factor K, which might be termed its modulus of plasticity, as in the formula

$$Px-KPy=\text{a constant}$$

It was found that, if the data are calculated so as to take into consideration the bulge of the cylinder and are plotted to show

vertical stress as compared with lateral stress, this formula represents the facts and that each of the softer rocks possesses a definite modulus of plasticity, this being also true in the harder rocks in the earlier stages of the deformation at least.

This interesting fact is discussed at length in the accompanying paper by Dr. King, where a mathematical treatment of some of the new data developed in the present investigation is also presented, illuminating certain parts at least of that hitherto unsubdued and almost unoccupied domain—the mathematics of the flow of solids.

In the present paper, without entering into a mathematical treatment of the subject, the following deductions from the experimental data may be indicated.

If a vertical line be drawn cutting off the "true curve" obtained in the case of any rock when the deformation of the tube amounting to 0.15 has been reached, and if the area inclosed by this line, the "true curve" itself, and the base line of the diagram be measured, this area represents the "work done" to effect the deformation of the rock. This area showing the "work done" in deforming a standard column of Carrara marble in a 0.25-centimeter steel tube in Fig. 7 is shaded. In Fig. 9 the "true curves" obtained in this deformation of all the rocks of the series, in steel tubes having a wall thickness of 0.25 centimeter, are shown, and in Fig. 10 the complete series of "true curves" obtained when the wall thickness of the tube is increased to 0.33 centimeter is set forth. In both figures the curves are cut off at the ordinate 0.15, and the area representing the "work done" in the case of each rock is clearly shown and may be compared.

Table III sets forth these comparative values in square inches. This table shows quite clearly that with the increased resistance, offered by the thicker-walled steel tube, the amount of work required to effect an equal deformation increased in the case of every rock. It also sets forth the comparative value of these increases and also the relative amount of work done to deform the different rocks of the series.

The table thus shows that the "work done" in deforming a column of marble of the size employed and under the conditions of the experiment, when inclosed in the thinner-walled tube, is to the "work done" when an identical column is deformed, when inclosed

in the thicker-walled tube, as 51,708 is to 60,415. Or, again, that the "work done" in deforming a marble column, whether the resistance be small or great, is almost exactly one-half of that required to effect an equal amount of deformation in a column of granite under the same conditions. That is to say, almost exactly twice as much work is required to deform granite as is required to effect an equal deformation in the case of marble and nearly four times as much as is required to produce an equal deformation in the case of steatite.

TABLE III

RELATIVE AMOUNT OF "WORK DONE" IN EFFECTING AN EQUAL DEFORMATION IN UNIT COLUMNS OF DIFFERENT ROCKS

	UNDER RESISTANCE OF	
	0.25 cm. Steel Tube	0.33 cm. Steel Tube
Steatite	26,054	34,123
Alabaster	35,569	42,946
Sandstone	41,262	53,446
Marble	51,708	60,415
Dolomite	66,362	77,092
Belgian Black	73,754	79,362
Slate	79,069	97,154
Diabase	92,985	107,431
Granite	104,169	119,877

TABLE IV

RELATIVE AMOUNT OF "WORK DONE" IN EFFECTING AN EQUAL DEFORMATION IN UNIT COLUMNS OF DIFFERENT ROCKS CALCULATED ON THE BASIS OF MARBLE AS UNITY

	UNDER RESISTANCE OF	
	0.25 cm. Steel Tube	0.33 cm. Steel Tube
Steatite	0.50	0.56
Alabaster	0.69	0.71
Sandstone	0.80	0.88
Marble	1.00	1.00
Dolomite	1.28	1.28
Belgian Black	1.43	1.31
Slate	1.53	1.61
Diabase	1.80	1.78
Granite	2.01	1.98

If the "work done" to deform marble be taken as unity, these figures may be set forth as in Table IV.

In these tables there is expressed in actual values the phenomena which are displayed in such a striking manner in the great exposures of the Grenville series and in other terranes which have undergone deformation at great depths below the surface of the earth where the same force has acted on a complex of rocks of diverse character. In these occurrences some of these rocks are torn to fragments, which are then carried far apart in a flowing matrix formed of some other and more plastic member of the complex. This is seen in a striking manner where dykes of diabase or belts of granite cut through a limestone, and the whole complex is then deformed under conditions of deep-seated differential pressure. The diabase dyke or belt of granite is torn apart into angular fragments, which are floated along in sinuous curves in the plastic flowing limestone, like logs or drifting timber on the surface of a flowing river (see Fig. 11).

EFFECT OF A CHANGE IN THE RAPIDITY OF THE APPLICATION OF PRESSURE

In Fig. 12 there are two curves: one showing the deformation of alabaster, the other, the deformation of marble. These also illustrate the effects of a change in the rate at which the pressure is applied.

In the former case, after a load of 36,000 pounds had been gradually applied in successive increments and no movement had taken place under the load for 2 minutes, the next increment of load was by mistake applied suddenly, thereby submitting the rock to an impact instead of to a slow increase of pressure. This, as will be seen, produced at once a movement of 0.045 inch. Following this, however, four increments of load, each of 1,000 pounds, had to be applied before the movement was resumed, and two additional increments, each of 1,000 pounds, had to be applied before the movement could be re-established in its regular course, after which the flow continued in the line followed by the normal curve.

In the second case—that of the marble—the normal course of the experiment was interrupted four times by postponing the time of reading the deformation produced by a new increment of load much longer than usual, namely, from 9 to 75 minutes. These were when the load on the column of rock was 40,000, 55,000,

60,000, and 65,000 pounds, respectively. It will be noted that the same effect, though on a smaller scale, was produced as that just described as the result of impact. An abnormal increase of load

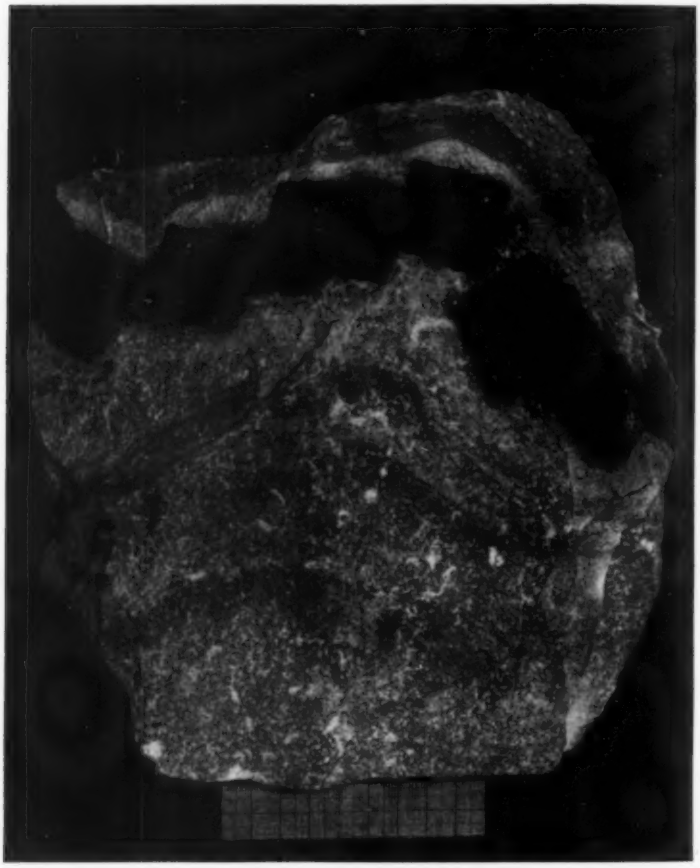

FIG. 11.—Photograph of a specimen of Trenton limestone which has been cut by a narrow dyke of camptonite. The whole has then been distorted by pressure exerted by the intrusion of the igneous mass constituting Mount Royal. The harder camptonite has been broken into fragments which have been carried apart in the flowing mass of more plastic limestone (Canadian Northern Railway Tunnel through Mount Royal, Montreal, Canada).

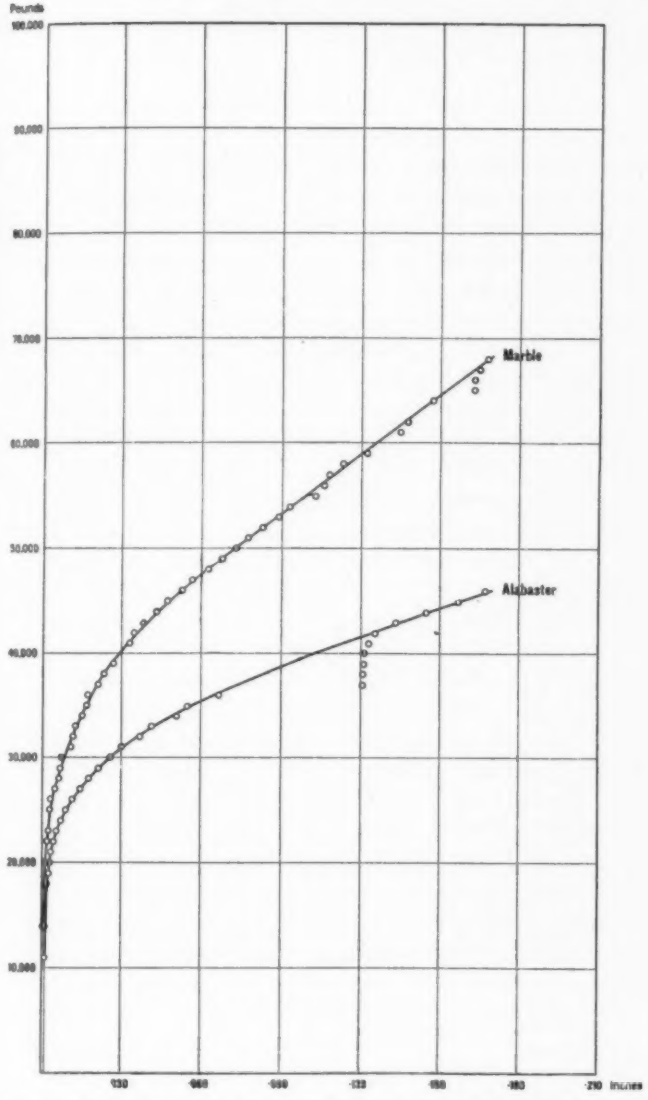

FIG. 12.—Curves showing the effect of change in rate of application of pressure

was required to bring about a re-establishment of the movement, which, however, eventually resumed its former course.

BEARING OF THE RESULTS ON CERTAIN PROBLEMS PRESENTED BY THE EARTH'S CRUST

The experimental results afford a reply to the question propounded by Dr. Gilbert and set forth in the opening paragraph of this paper. They also have a direct bearing on the problems presented by the origin of "decken" and by the theory of isostasy.

When movement producing deformation is once started in the rock under the influence of tangential thrust, resulting in the breaking down of its texture, the rock, if deeply buried in the earth's crust, does not on that account offer a decreased resistance to further movement.

Some experiments by Karman[1] on the deformation of marble under differential pressure have yielded data with reference to the amount of this pressure which must be exerted in the case of marble in order to induce plastic flow in the rock. The data obtained represent maximum results, because in the experiments the pressure was applied rapidly as compared with that which would be developed in any earth movements, and, also, the factor of heat was not taken into account. It must be noted, however, that heat and a very slow application of the deforming force would produce movements under lower pressures than those made use of in the experimental work. Karman found that, if a column of marble were submitted to a supporting or containing pressure, such as that exerted by the steel tube in our experiments, amounting to 685 atmospheres—which would be equivalent to that exerted by the overlying strata at a depth of 2.53 miles below the surface[2]—it would flow uniformly and continuously under a load of 2,870 atmospheres applied to the ends of the column. If the containing pressure fell below the value mentioned, that is, if the rock occupied a position in the earth's crust nearer the surface, it would speedily crumble and break to pieces, presenting in this way a failure similar

[1] "Festigkeits Versuche unter allseitigem Druck," *Zeit. des Ver. deut. Ingenieure*, October 21, 1911.

[2] F. D. Adams, "Depth of the Zone of Flow in the Earth's Crust," *Journal of Geology*, February, 1912.

to that which is obtained in testing building stones in the laboratory. On the other hand, if the containing or supporting pressure is increased, the load required to produce deformation rapidly increases also, and the experiments seem to indicate that with a containing pressure of about 10,000 atmospheres, which would be equivalent to a depth of about 22 miles below the surface, it would be impossible to make the marble flow, except under a pressure which would be simply colossal.

Since with the increase of resistance to tangential thrust, that is, with increasing depth below the surface of the earth, the amount of such thrust required to produce movements in the earth's crust increases rapidly, it is evident that the great movements of adjustment by rock flow or transference of material in the earth's crust from one point to another—other than the transference of rock in a molten condition—must take place comparatively near the surface. That is, beneath the zone of fracture where adjustment takes place by faults and overthrusts—in the zone of flow—movements so far as they are determined by pressure are effected with an ease which increases rapidly in proportion to their nearness to the surface.

It would seem, therefore, that it is in the upper part of the zone of flow only that the great "decken," as, for instance, those which are developed in the Alps, are produced. This explains the fact that in the mountain range in question it is the upper "decken" which have moved more rapidly and have extended farther than the lower "decken," where the rock is under the increased load and is consequently much less plastic.

Since with the increase of depth there is a rapid increase in rigidity of the rocks of the earth's crust, it is not difficult to understand how it is that, while great movements may take place near the surface of the earth in the upper part of the zone of flow, the globe itself is "more rigid than steel or glass."

The experimental work also affords at least a first approximation to the determination of the dimensions of the forces which are required in order to effect deformation in the earth's crust in the case at least of the chief types of rocks which make up the crust in question.

In these measurements it must again be noted that the factor of pressure alone was considered, no account being taken of the element of heat in the crust, which would undoubtedly tend to increase the ease of movement.

In the experiments it has been shown, as mentioned, that the resistance to deformation exerted by the wall of the steel tube gradually increases as the experiment progresses. If, however, the value of the resistance is taken at a point where the regular column shows a diametral increase of 0.05 inch (or 6.35 per cent), i.e., when the deformation is well under way and after which it becomes proportional to the increased tangential pressure, this resistance, in the case of the experiment with the steel wall 0.25 centimeter thick, would be equivalent to 26,685 pounds to the square inch, or 1,815 atmospheres, that is, to a depth of 4.2 miles below the surface.

In the case of our experiment with a steel wall 0.33 centimeter thick it would be equivalent to 37,359 pounds per square inch, or 2,542 atmospheres, that is, to a depth of 5.8 miles below the surface.

Thus at these respective depths the additional tangential thrust required to induce a pronounced movement in the case of marble and granite, respectively, would be as shown in Table V.

TABLE V

	At Depth of 4.2 Miles		At Depth of 5.8 Miles	
	Pounds per Square Inch	Atmospheres	Pounds per Square Inch	Atmospheres
Marble	66,400	4,517	74,500	5,068
Granite	138,500	9,422	159,600	10,857

CONCLUSIONS

1. All the rocks employed in the present investigation can be deformed under differential pressure at ordinary temperatures.

2. In order to effect an equal deformation, it is necessary to employ differential pressures having different values in the case of the several rocks.

3. The ease with which these rocks are deformed has as one of its functions the hardness of the rock (or of the minerals composing it).

4. In the case of the softer rocks—alabaster, steatite, marble, etc.—the deformation is produced by movements due to a slipping within the constituent crystals of the rock on their gliding planes, often accompanied by twinning, the movement in this case being similar to that seen in metals when they are deformed. In the harder rocks the deformation is accompanied by granulation, the texture developed being similar to that found in mylonite.

5. Each of the softer rocks at least has a well-defined modulus of plasticity.

6. The "work done" when a rock is deformed by a tangential thrust, within the earth's crust, increases rapidly with the weight of the superincumbent strata, i.e., with its depth below the surface.

7. The relative ease with which the several rocks will flow under differential pressure is shown in Tables III and IV, which give mathematical expression of the "work done" in deforming standard columns of each rock.

8. A uniform thrust exerted on a prism of the earth's crust may deform and fold the upper portion of the mass, while it will be quite insufficient to produce any movement in the lower part of the same mass.

9. The thrust required to develop deformation, taking no cognizance of the influence of heat or the time effect which might result if the pressure were applied with extreme slowness, in the case of marble, and of granite, is shown by the values given in Table V.

10. To revert to the question propounded by Dr. Gilbert, in order to develop flow in any rock within the earth's crust the rock must be submitted to a differential stress which is greater than that which is required merely to break down its texture and very much greater than that which is sufficient to crush it to pieces under the ordinary conditions which obtain at the surface of the earth.

ON THE MATHEMATICAL THEORY OF THE INTERNAL FRICTION AND LIMITING STRENGTH OF ROCKS UNDER CONDITIONS OF STRESS EXISTING IN THE INTERIOR OF THE EARTH

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INTRODUCTION

That solid bodies could be permanently deformed and made to flow without rupture under sufficiently great stress has long been known. The extensive experiments of Tresca on the flow of metals[1] (1864–72) directed the attention of several mathematicians of the time to the subject. Tresca announced as a result of his experiments the simple law that a stressed solid would commence to flow as soon as the maximum shearing stress exceeded a limiting value K characteristic of the solid. This hypothesis was incorporated into the elastic solid theory by Saint-Venant[2] and others. The hope was expressed by these writers that by effecting the solution of simple problems in "plasticodynamics," corresponding to the experimental arrangements employed, it might be possible, not only to verify the theoretical results, but also to determine a specific constant K characteristic of the various metals and related in an intimate manner to other physical constants. It was found possible, however, to solve only a very limited number of extremely simple problems: (1) circular cylinder under uniform pressure over the plane ends or subject to uniform lateral pressure; (2) cylindrical shell constrained to remain of constant length and subject to uniform internal and external pressure; (3) circular cylinder twisted beyond the elastic limit; (4) bar of rectangular section bent by a suitable distribution of forces to take the form of a circular arc.

[1] H. Tresca, *Par. Mém. Sav. Etr.*, XX (1872), 75 ff. and 281 ff. A summary of Tresca's experiments is given by L. S. Ware, *Journal of the Franklin Institute*, LXXIII (1877), 418 f.

[2] Saint-Venant, *Comptes Rendus*, LXVII (1868), 131 ff., 203 ff., 278 ff.; LXVIII (1869), 221 ff., 290 ff.

None of these simple problems corresponded, however, to any detailed observations available. The position with regard to the final mathematical interpretation of Tresca's observations was summed up by Saint-Venant in a communication to the French Academy.[1] It was stated that, before much progress could be made in formulating a mathematical theory of plastic flow, it would be necessary to plan experiments more easily capable of mathematical specifications; in particular he recommended that means be taken to trace out in the *interior* of the solid the extent of the plastic deformations. The difficulty of doing this without at the same time interfering with the continuity of the solid under test has apparently not been overcome up to the present, so that data on plastic deformation available for mathematical treatment are still very meager.

It is interesting to notice, however, that we have available at the present day a method of exploring the internal structure of solids which seems to fulfil the need expressed by Saint-Venant. By the use of extremely powerful X-rays it has been found possible to detect internal cavities in steel castings not visible on the surface. The subject has recently been extensively studied by Davey,[2] who states that it is possible to detect an air-inclusion 0.021 inch thick in $1\frac{1}{4}$ inches of steel and an air-inclusion 0.007 inch thick in $\frac{5}{8}$ inch of steel. More recently Pilon,[3] making use of the Coolidge tube, has successfully penetrated 5.5 centimeters of steel. This method appears to the writer to offer the means of studying in successive stages the plastic deformation of specimens of various materials under conditions of intense stress. In these circumstances it would be necessary only to drill extremely fine holes in the specimen in various directions and to study the deformation of these as the solid is made to flow.

Tresca's hypothesis that flow in a solid commences and continues as long as the shearing stress exceeds a definite limit has been found

[1] Saint-Venant, "De la suite qu'il serait nécessaire de donner aux recherches expérimentales de plasticodynamique," *Comptes Rendus*, LXXXI (juillet, 1875), 115–21.

[2] W. P. Davey, *Trans. Am. Electrochem. Soc.*, XXVIII (1915), 407–18.

[3] H. Pilon, *Rev. de Mét.*, XII (Nov., 1915), 1017–23.

by later tests to be only approximately true. It is found that to produce continuous flow in a plastic solid it is necessary continuously to increase the distorting stress. A simple illustration of this fact is to be noticed in the manner in which a short circular cylinder crushed in a testing machine ultimately breaks down. According to Tresca's theory the surfaces of shear should be cones of semi-vertical angle of 45°, while experiments indicate that the angle is more often in the neighborhood of 55° for a material like cast iron.[1] These results have led to a modification of Tresca's hypothesis as already mentioned. The effect of this so-called "resistance to flow" does not appear to have been studied with a view to formulating the laws according to which solids may be made to flow continuously.

In the field of experimental ballistics the use of the permanent deformation of short copper cylinders to measure the enormously high pressures involved in testing explosives by means of the so-called "crusher-gauge," invented by Noble about 1875,[2] has led to the detailed study of the relation of applied stress and deformation produced in these special circumstances.[3] The results of these observations have recently been studied in detail by Brillouin.[4] The behavior of copper shows the existence of internal friction analagous to that observed by Adams and Bancroft in the case of various rock specimens.

In the experiments carried out by the latter investigators the use of nickel-steel jackets of standard thickness to incase the rock specimens subjected to flow is analagous to the use of short cylinders of annealed copper in the crusher-gauges just referred to. In order to obtain the lateral pressure on the specimen corresponding to a given deformation of the nickel-steel jacket, a calibration-curve is obtained by filling the cylinders with tallow. The hydrostatic pressures required to give a series of deformations give the required

[1] A. Morley, *Strength of Materials* (Longmans, Green, & Co., 1908), p. 55.

[2] See *Encyclopaedia Britannica*, 11th ed., article on "Ballistics," for a brief description of the crusher-gauge.

[3] Vieille, *Mémorial des poudres et salpêtres* (Gauthier-Villars, Paris),V, 12–61.

[4] M. Brillouin, "Les grandes déformations du cuivre par écrasement et par traction," *Ann. de Chimie et de Physique*, 9e série, II (1914), 489–96.

calibration-curve, just as the copper cylinders of the crusher-gauge are calibrated under known end pressures in a testing machine.

MATHEMATICAL DISCUSSION OF THE OBSERVATIONS OF ADAMS AND BANCROFT DURING THE ELASTIC STAGE

Although the experiments which form the subject of the present discussion were all carried out when both rock and nickel-steel had been deformed beyond the elastic limit, it is not without interest, especially in view of further experiments on the subject, to follow out the distribution of stresses in the rock specimen and in the nickel-steel throughout the elastic stage. The necessary theory from which the formulas given below are derived has been given by the writer in a previous paper.[1] As in that discussion, it is sufficient for the present purpose to consider the ideal problem of plane stress, that is, one in which the end pressures and lateral pressures are such that the displacements at the outer surfaces, both of the rock specimen and of the nickel-steel jackets, are everywhere symmetrical with respect to the axis and everywhere constant for a given load. In reality the nickel-steel jacket shows a bulge over the center of the specimen. As long as this is not too great the analysis will give an approximate representation of the state of stress in the central portion of the specimen and nickel-steel jacket at which the measurements of displacement were taken by means of a sensitive extensometer. The justification for this mode of treatment has already been noticed in the writer's paper previously referred to in its application to a similar problem.

We denote by $\widehat{rr}$ the stress component along the radius r; by $\widehat{\theta\theta}$, the component at right angles to r; and by $\widehat{zz}$, that along the axis. According to Lamé's notation, μ is the modulus of rigidity of the rock specimen and λ one of the moduli of elasticity such that $\kappa=(\lambda+\frac{2}{3}\mu)$ is the modulus of compression. Poisson's ratio is denoted by $\sigma=\frac{1}{2}\lambda/(\lambda+\mu)$. We denote by accented symbols the corresponding elastic constants for nickel-steel. In the problem under discussion we denote by b the radius of the rock specimen and

[1] L. V. King, "On the Limiting Strength of Rocks under Conditions of Stress Existing in the Earth's Interior," *Journal of Geology*, XX (February–March, 1912), 121–26.

the interior radius of the nickel-steel jacket, and by c the exterior radius of the nickel-steel jacket. If P is the pressure per unit area applied to the end of the test specimen, we have $\widehat{zz}=-P$. The principal shearing stresses are one-half the algebraic difference of the principal stresses and are at once obtained by writing $a=0$ in the equations (13) of the writer's paper mentioned above. We then obtain

$$\left.\begin{aligned} &\text{(i)} \quad \tfrac{1}{2}\,|\,\widehat{rr}-\widehat{zz}\,| = \tfrac{1}{2}\,\frac{\sigma}{1-\sigma}\,P\left\{\frac{1-2\sigma}{\sigma}+\frac{\beta}{1+\beta}\right\} \\ &\text{(ii)} \quad \tfrac{1}{2}\,|\,\widehat{rr}-\widehat{\theta\theta}\,| = 0 \\ &\text{(iii)} \quad \tfrac{1}{2}\,|\,\widehat{\theta\theta}-\widehat{zz}\,| = \tfrac{1}{2}\,\frac{\sigma}{1-\sigma}\,P\left\{\frac{1-2\sigma}{\sigma}+\frac{\beta}{1+\beta}\right\} \end{aligned}\right\} \qquad (1)$$

where

$$\beta=\frac{1+\sigma}{1-\sigma}\cdot\frac{\mu}{\mu'}\left\{1+\frac{1-\sigma'}{1+\sigma'}\,\frac{b^2}{c^2}\right\}\cdot\frac{1}{1-b^2/c^2} \qquad (2)$$

The radial displacement U at the outer surface of the rock specimen is given by

$$\frac{U}{b}=\frac{P}{2\mu}\cdot\frac{\sigma}{1+\sigma}\,\frac{\beta}{1+\beta} \qquad (3)$$

Each of the principal shearing stresses (i), (ii), (iii), is associated with a family of surfaces along which the material will crack or flow. These are illustrated in Fig. 1, reproduced from the writer's paper already mentioned. It is important to notice in the present connection that the principal shearing stresses in the interior of the rock, as given by (i) and (iii), are independent of the radius r and remain equal throughout the elastic régime. It thus follows from Tresca's theory that the rock, when stressed under these ideal conditions, will commence to break down or flow *simultaneously* throughout its entire volume. The surfaces of shear which will be associated with the elastic breakdown may either be the system of cones (i) of semivertical angle 45° or the system of helicoidal surfaces (iii) of 45° pitch giving rise to the well-known Luder's lines on the curved surface of the specimen. The particular surfaces of shear which will be observed in any particular test will depend on accidental circumstances, as either system is equally likely to occur.

We easily derive expressions for the principal shearing stresses in the nickel-steel jacket. At points distant r' from the axis these are

$$\left.\begin{aligned}
&\text{(i)}' \quad \tfrac{1}{2}\,|\,\widehat{rr}'-\widehat{zz}'\,| = \tfrac{1}{2}P\cdot\frac{\sigma}{1-\sigma}\cdot\frac{1}{1+\beta}\,\frac{c^2/r'^2-1}{c^2/b^2-1}\\
&\text{(ii)}' \quad \tfrac{1}{2}\,|\,\widehat{rr}'-\widehat{\theta\theta}'\,| = P\frac{\sigma}{1-\sigma}\,\frac{1}{1+\beta}\,\frac{c^2/r'^2}{c^2/b^2-1}\\
&\text{(iii)}' \quad \tfrac{1}{2}\,|\,\widehat{\theta\theta}'-\widehat{zz}'\,| = \tfrac{1}{2}P\,\frac{\sigma}{1-\sigma}\,\frac{1}{1+\beta}\,\frac{c^2r'^2+1}{c^2/b^2-1}
\end{aligned}\right\} \qquad (4)$$

The radial displacement U' at the outer surface of the nickel-stee jacket is given by

$$\frac{U'}{c}=\frac{P}{\mu'}\cdot\frac{b^2}{c^2}\cdot\frac{1}{1-b^2/c^2}\cdot\frac{1'}{1+\sigma'} \qquad (5)$$

By writing $\mu=0$ and therefore $\beta=0$, $\sigma=\frac{1}{2}$, the foregoing give the familiar results for stresses in a cylinder subject to internal hydro-

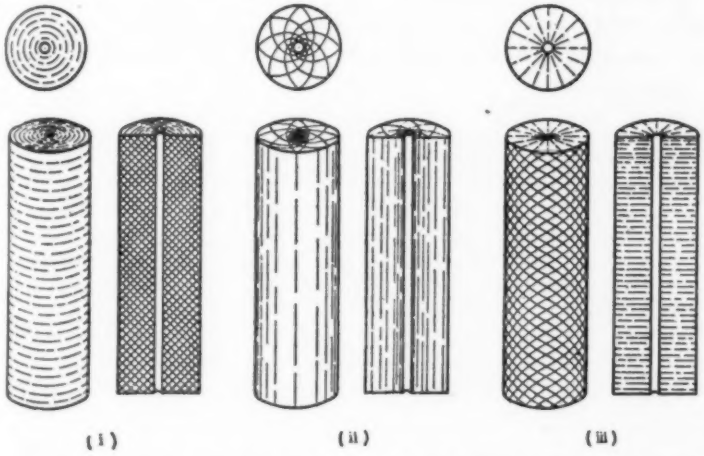


FIG. 1.—(Figure from this Journal, Vol. XX, No. 2 [February-March, 1912], p. 123.)

static pressure. The three principal shearing stresses given above all take their maximum value (independent of sign) at the interior

surface $r=b$, and of these maxima (ii)$'$ is the greatest. The maximum shearing stress is therefore

$$\tfrac{1}{2}\,|\,\widehat{rr}'-\widehat{\theta\theta}'\,|_{max.}=P\frac{\sigma}{1-\sigma}\cdot\frac{1}{1+\beta}\cdot\frac{1}{1-b^2/c^2} \qquad (6)$$

It follows from this discussion that elastic breakdown of the nickel-steel jacket commences at the interior surface and, as deformation continues, extends gradually to the outer surface. The surfaces of shear in this case are the system of cylindrical surfaces whose traces on a plane perpendicular to the axis of the cylinder are equiangular spirals intersecting orthogonally and cutting all radii at angles of 45°. An examination of the nickel-steel jackets shows, in fact, that the surfaces of shear approximated roughly to this system. The polished outer surface of stressed specimens showed indications of fine longitudinal ribs, while in such as were actually ruptured it was noticed that the surface of rupture conformed to that predicted from theory. As the rupture occurred when the nickel-steel was stressed very much beyond the elastic limit, the actual surfaces of shear are determined by very complex conditions involving the effect of internal friction, with which we shall deal in a later section.

Numerical results.—A rough verification of the preceding results may be made by calculating the relation between the load and the increase of diameter of the nickel-steel jacket according to equation (5). For nickel-steel we take $\sigma'=0.327$ and $\mu'=10.8\times10^6$ pounds per sq. in., values employed in the writer's paper just referred to. In one set of experiments (referred to as 0.25-centimeter wall) $b=1.00$ cm., $c=1.25$ cm., giving from (2)

$$\beta=3.68\times\frac{1+\sigma}{1-\sigma}\cdot\frac{\mu}{\mu'}.$$

When the jacket is filled with tallow we may take $\sigma=\frac{1}{2}$, $\mu=0$, $\beta=0$, so that equation (5) gives

$$U'/c=1.34\times(P/\mu'),$$

or in terms of the total load, $W=\pi b^2P$, we obtain

$$2U'\text{ (inches)}=2.52\times10^{-7}\times W\text{ (pounds)} \qquad (7)$$

When a specimen of Carrara marble is inserted we have[1] $\sigma=0.2744$, $\mu=3.154\times10^6$ pounds per sq. in., whence $\beta=1.889$ and

$$U'/c=0.176\times(P/\mu'), \text{ or } 2U' \text{ (inches)}=3.31\times10^{-8}\times W \text{ (pounds)} \quad (8)$$

In another set of experiments (referred to as 0.33-centimeter wall), $b=1.00$ cm., $c=1.33$ cm., giving

$$\beta=2.96\times\frac{1+\sigma}{1-\sigma}\frac{\mu}{\mu'}.$$

In the case of tallow filling we find as before,

$$U'/c=0.980\times(P/\mu') \text{ or } 2U' \text{ (inches)}=1.96\times10^{-7}\times W \text{ (pounds)} \quad (9)$$

and in the case of the Carrara marble specimen

$$U'/c=0.147\times(P/\mu') \text{ or } 2U' \text{ (inches)}=2.94\times10^{-8}\times W \text{ (pounds)} \quad (10)$$

In Fig. 2 are compared the observed and theoretical stress-strain diagrams corresponding to the cases calculated out in equations (8) to (10). In the case of tallow filling, the initial slope of the observed curves agrees approximately with the calculated slope. In the case of the marble filling, the agreement is within the limits of error involved in measuring these extremely small strains.

MATHEMATICAL DISCUSSION OF THE OBSERVATIONS OF ADAMS AND BANCROFT DURING THE PLASTIC STAGE

1. *Navier's theory of internal friction.*—Let $\widehat{xx}$, $\widehat{yy}$, and $\widehat{zz}$ be the principal stresses in the solid at a point P measured toward the origin (Fig. 3). Let S be the shearing stress in a plane whose direction cosines with respect to the direction of the three principal stresses are (l, m, n). Let N be the stress normal to this plane. We then have

$$\left.\begin{aligned} S^2+N^2&=l^2\widehat{xx}^2+m^2\widehat{yy}^2+n^2\widehat{zz}^2 \\ \text{and} \qquad N&=l^2xx+m^2\widehat{yy}+n^2\widehat{zz} \end{aligned}\right\} \quad (11)$$

Generalizing somewhat on Navier's hypothesis of elastic breakdown, we may state that the material will not break down as long as

$$S<K \quad (12)$$

[1] Adams and Coker, "Elastic Constants of Rocks," *Publication No. 46 of the Carnegie Institution of Washington*, 1906, p. 69.

where K is a function, not only of the stress N normal to the plan at which slide occurs, but also of the previous history of the

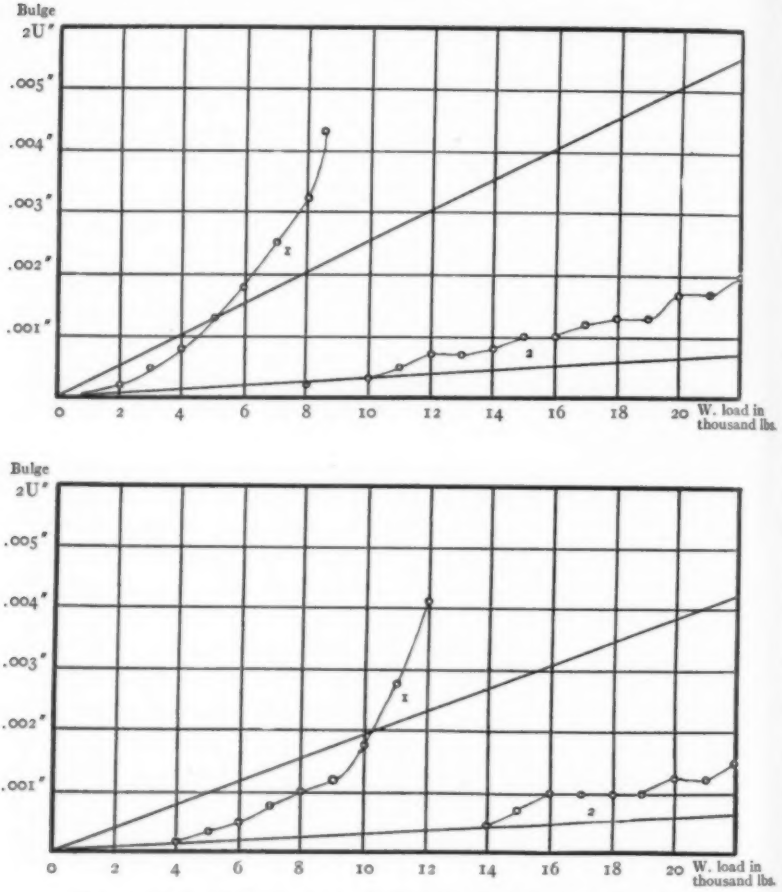


FIG. 2.—Theoretical and observed stress-strain diagrams. Curves 1, tallow filling. Curves 2, Carrara marble filling.

specimen. According to Tresca's hypothesis, K was regarded as a constant, depending only on the nature of the specimen. An exten-

sion of this hypothesis due to Navier (the so-called internal-friction theory) replaces (12) by the condition

$$S<K+\mu N,$$

μ being a new constant somewhat analogous to the coefficient of friction of mechanics. In order to discover the relation between the principal stresses at the elastic limit, it is necessary to find the direction (l, m, n) which makes $(S-\mu N)$ a maximum and equate the result to K. Suppose the principal stresses to be all of the same sign, two of them equal, $\widehat{yy}=\widehat{xx}$, and $\widehat{zz}>\widehat{xx}$ (corresponding to the state of affairs in the cylindrical rock specimens under test). We then have, writing $l=\sin\theta\cos\phi$, $m=\sin\theta\sin\phi$, $n=\cos\theta$,

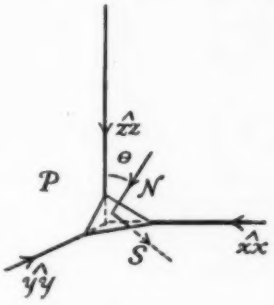


FIG. 3

$$\left.\begin{aligned} S^2+N^2&=\widehat{xx}^2\sin^2\theta+\widehat{zz}^2\cos^2\theta, \quad N=\widehat{xx}\sin^2\theta+\widehat{zz}\cos^2\theta \\ S&=(\widehat{zz}-\widehat{xx})\sin\theta\cos\theta \end{aligned}\right\} \tag{13}$$

$$S-\mu N=(\widehat{zz}-\widehat{xx})\sin\theta\cos\theta-\mu(\widehat{xx}\sin^2\theta+\widehat{zz}\cos^2\theta) \tag{14}$$

This expression reaches a maximum when

$$\cot 2\theta=-\mu, \tag{15}$$

in which circumstances

$$(S-\mu N)_{max.}=\tfrac{1}{2}(\widehat{zz}\cot\theta-\widehat{xx}\tan\theta), \tag{16}$$

and the relation between the principal stresses at breakdown is given by

$$\widehat{zz}=2K\tan\theta+\widehat{xx}\tan^2\theta \tag{17}$$

where θ is given in terms of μ (the coefficient of friction) by (15). This result indicates that the material in question will break down along a family of cones of semivertical angle $\alpha=\frac{1}{2}\pi-\theta$.

2. *Discussion of observations.*—In the experiments of Adams and Bancroft the cylindrical rock specimens were subjected to end loads transmitted by the steel pistons. As a result of the intense pressure

developed, the rock cylinders were caused to bulge out laterally over the central portion, where the thickness of the nickel-steel jacket was reduced to 0.25 centimeter and 0.33 centimeter, respectively, in the two sets of experiments. The rock was thus subjected to a continuous succession of breakdowns, so that it was possible from these observations to determine the relation between the end and lateral pressures required to keep the rock in movement.

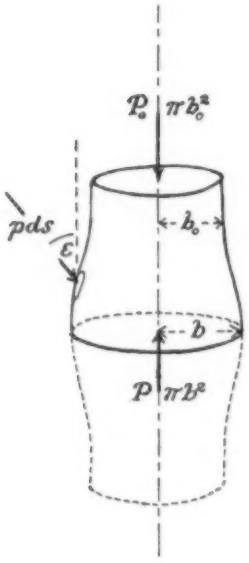


FIG. 4

Considering the central portion of the rock cylinder throughout which the flow takes place, we may reasonably assume, when the bulge is small, that the average pressure-intensity P_o along the direction of the axis is given by

$$P_o = W_o/(\pi b_o^2),$$

W_o being the load on the steel piston and b_o its radius. As the bulge becomes sensible, it is necessary to make a correction to allow for the increasing area over which the pressure is distributed. Referring to Fig. 4, we denote by P the average pressure-intensity across a plane at right angles to the axis at the position of maximum bulge where the radius of the cross section is b. We denote by p the resultant traction per unit area exerted by the nickel-steel jacket on the rock specimen in a direction making an angle ϵ with the axis. Then, considering the equilibrium of one-half of the rock specimen, we may write

$$\pi P_o b_o^2 + \int p \cos \epsilon \, dS = \pi b^2 P, \tag{18}$$

the integral representing the total component of the tractions between the rock specimen and the nickel-steel jacket in a direction parallel to the axis of the cylinder. When an exactly similar jacket is filled with tallow and deformed by the application of a load on the steel pistons in the same way, we may consider the pressure in

the interior to be hydrostatic. If p_0 be the hydrostatic pressure required to bulge the nickel-steel jacket to the same radius b, we have instead of (18) the equation

$$\pi p_0 b_0^2 + \int p_0 \cos \epsilon_0 dS = \pi b^2 p_0, \tag{19}$$

where ϵ_0 now denotes the direction which the normal to the deformed surface makes with the axis of the cylinder. It was carefully ascertained in the experiments of Adams and Bancroft that the *shape* of the bulged nickel-steel jacket was the same when occupied by the softer rocks and such an easily flowing metal as lead, in which conditions of pressure approach very nearly to hydrostatic conditions under the very intense loads employed. As the deformation of the nickel-steel jacket is due to the distribution of surface tractions p, it is reasonable to assume that they are distributed in approximately the same way. This is equivalent to asserting that the tangential component of the surface traction between rock and nickel-steel is negligible compared to the normal component, a statement which seems to be reasonable in view of the fact that both rock and nickel-steel are highly polished over the surface of contact. We may thus write $\int p \cos \epsilon \, dS = \int p_0 \cos \epsilon_0 \, dS$ in (18) and (19) and arrive at the relation

$$P = p_0(1 - b_0^2/b^2) + P_0 b_0^2/b^2, \tag{20}$$

giving the average pressure-intensity at the center of the specimen to be identified with $\widehat{zz}$ of equation (17). The corresponding lateral pressure is given by p_0, which is identified with $\widehat{xx}$ of (17).

We are now in a position to test the theory of internal friction expressed by (17) from the observations of Adams and Bancroft. It is only necessary to plot against each other the end pressures $\widehat{zz}$ and the lateral pressures $\widehat{xx}$ as determined above. Such specimens as give straight lines may be said to possess a definite *modulus of plasticity*, K, and *coefficient of internal friction*, μ. Curves obtained in this way are shown in the Appendix, where they are described in detail for the various specimens tested. The results show that for some kinds of rock the curves approximate closely to straight lines between certain limits of pressure. In the interpretation of these curves it must be kept in mind that the material is not broken

down from an initially unstrained state[1] at each stage of the process. The constants of plasticity and internal friction, as determined by the present investigation, refer to rock which is being made to flow continuously. This state of affairs, however, approaches more nearly to that occurring in nature during slow geological deformations than to conditions existing when the rock is broken down from an initially unstrained state.

Under ideal conditions the curves for the observations taken with the nickel-steel jackets of the two wall thicknesses should be identical. Actually, however, they differ to some extent, indicating that the effect of stresses set up by the deformation of the nickel-steel has not been entirely eliminated. The two sets of observations are, however, sufficiently close to give approximate estimates of the relation between the principal stresses which must exist before the rock can be made to flow under conditions existing in the earth's crust. It will be noticed from the curves of Plate I that for the harder rocks, such as diabase and granite, the curves along which breakdown takes place show the existence of a very large coefficient of internal friction. Since the hydrostatic pressure is given by $\frac{1}{3}(2\widehat{xx}+\widehat{zz})$, this is equivalent to the statement that the *stiffness* or limiting shearing stress required to break down the rock increases with the hydrostatic pressure to which the rock is submitted. In other words, we come to the important conclusion that *the stress-difference required to break down rock material under conditions of pressure existing in the earth's crust increases with the depth.* In the application of this result to geophysical problems, the foregoing conclusion may have to be somewhat modified to take into account the rise of temperature with depth. It is highly desirable that further experiments be carried out with a view to ascertaining the influence of this factor.

NOTE ON APPLICATIONS TO GEOPHYSICAL PROBLEMS

Up to the present the only quantitative data available for use in geodynamical problems have been obtained by crushing cubes of various rocks in a testing machine according to the ordinary rules

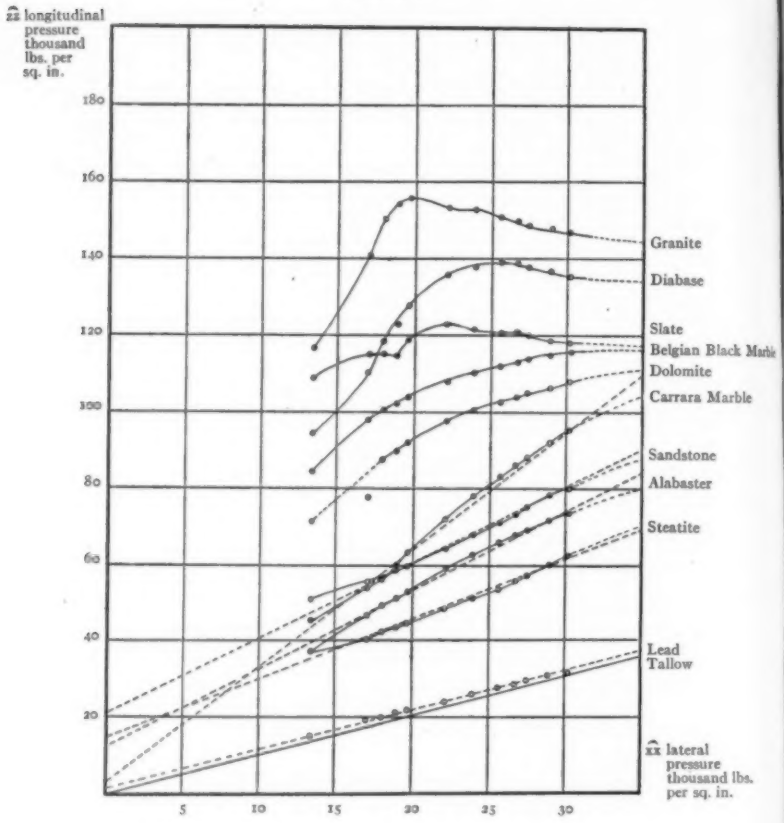
[1] Compare Karman's observations on marble and sandstone, *Zeit. des Vereins deutscher Ingenieure*, October 21, 1911.

of engineering practice. The unsatisfactory nature of such data as applied to conditions of stress deep down in the earth's crust has already been pointed out by the writer.[1] The results now available from the observations of Adams and Bancroft supply much needed data for the purposes of geophysics. Quoting from a classical paper by Sir George Darwin,[2] "With regard to the earth we require to know what is the limiting stress-difference under which a material takes permanent set or begins to flow rather than the stress-difference under which it breaks; for if the materials of the earth were to begin to flow, the continents would sink down, and the sea bottoms rise up." In the paper quoted Darwin estimates roughly the stress-difference in the interior of the earth due to a distribution of continental masses corresponding roughly to the actual distribution. For instance, it is estimated that the stress-difference under the continents of Africa and America is at a maximum at more than 1,100 miles from the earth's surface and amounts to about 4 tons per square inch. Darwin's conclusion that "marble would break under this stress, but that *strong* granite would stand" must be modified considerably in the light of the results of Adams and Bancroft, as the limiting strength of the rock material under the enormous pressure at the depth referred to would probably be increased many times. For the purposes of such calculations the curves of Plate I may be employed as they stand. If, for instance, it is desired to investigate the stability of mountain ranges or of continental elevations, the principal stresses at great depths must be derived from the theory of elasticity, making use of elastic constants derived from the interpretation of seismological records. If the principal stresses at any point be plotted as $\widehat{zz}$ and $\widehat{xx}$ on such a diagram as that of Plate I, a particular rock material will flow if the point falls between the axis $\widehat{zz}$ and the curve characteristic of the particular rock formation under consideration. The material will be on the point of flowing if the point falls on the curve itself, while the rock will stand the stress if the point falls between the

[1] L. V. King, *op. cit.*, p. 120.

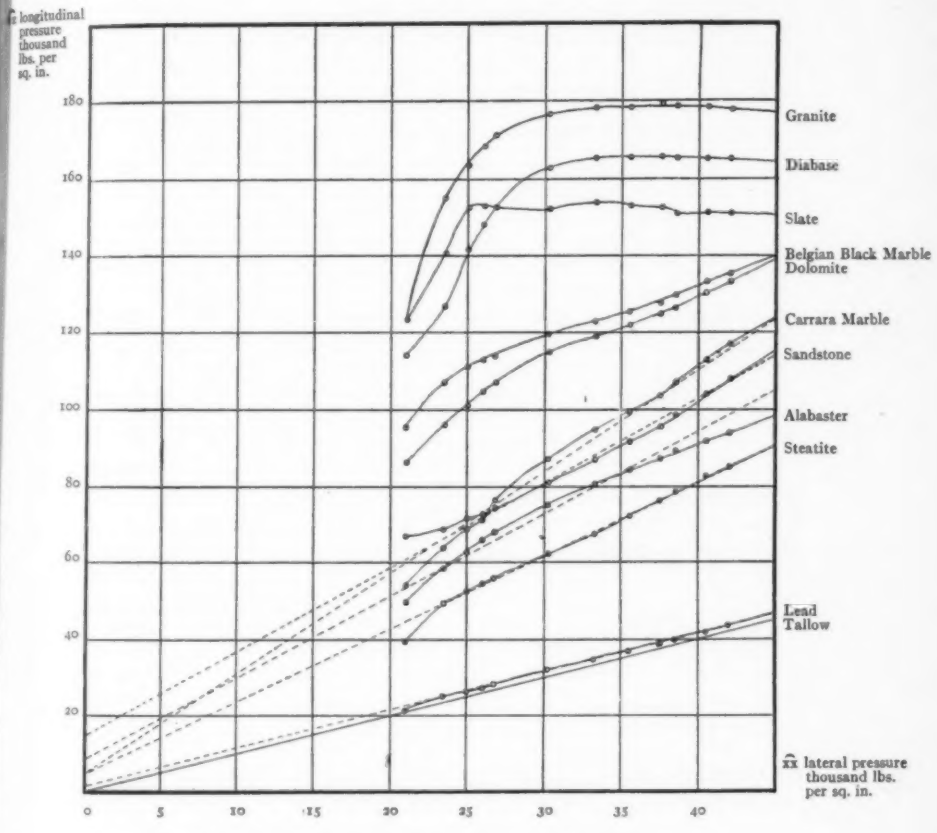
[2] Sir G. Darwin, "On the Stresses Caused in the Interior of the Earth by the Weight of Continents and Mountains," *Phil. Trans.*, CLXXIII (1882), 187–230; *Scientific Papers*, II (1908), 495.

PLATE I



RELATIVE PLASTICITIES OF VARIOUS ROCK SPECIMENS
Nickel-steel jackets of 0.25 cm. wall

PLATE II



RELATIVE PLASTICITIES OF VARIOUS ROCK SPECIMENS
Nickel-steel jackets of 0.33 cm. wall

curve and the axis $\widehat{xx}$. Thus for complete stability the entire series of points representing stress-differences beneath a continental elevation must fall in this latter region. It is thus evident that the existing theories of isostasy should, in considering the equilibrium of stresses called into existence by continental elevations and mountain ranges, take account of a "*compensation* of *plasticity*"—i.e., of the increased stiffness or resistance to deformation—of the underlying rock when submitted to greater hydrostatic pressure. With the reservation already made as to the possible influence of temperature, we have a considerable basis of evidence in favor of the conclusion that at any time in the past history of the earth continental elevations might have attained much greater altitudes above sea-level than any at present existing, without giving rise to stress-differences in the earth's interior sufficiently great to have caused rupture or breakdown, owing to the much increased "resistance to flow" set up in the rock material by the great pressure of the overlying crust. We should conclude also that, in the event of flow occurring, the region of flow would be confined to a region of the earth's crust comparatively near the earth's surface. The increasing limiting stress, with pressure characteristic of rock material made to flow as in Adams' and Bancroft's experiments, leads one to the conclusion that great movements of the earth's crust have for the most part always proceeded by extremely slow and continuous adjustments to pressure conditions, and not, as supposed by some geologists,[1] by a series of cataclysmal collapses of the type which would occur if the material of the earth's crust possessed in all circumstances a unique and definite limiting strength analogous to that obtained by crushing a specimen, unsupported laterally, in a testing machine. The further consideration of these problems must, however, be left over for further discussion. Enough has been said to make it evident that the results of Adams and Bancroft have provided much needed data in the light of which many of the existing theories of geodynamics may require considerable modification.

[1] G. A. J. Cole, Presidential address delivered before the geological section of the British Association, Manchester meeting, 1915, *B. A. Report*, pp. 403–20.

APPENDIX

In order to study the experimental data on the flow of rocks in the light of a theory of internal friction, the data reproduced in Tables I and II were obtained from the original large-scale curves obtained by Adams and Bancroft connecting the end load on the steel pistons with the bulge of the nickel-steel jacket. Each of the curves represented the mean of two, three, or more complete sets of observations. The first row of numbers for each specimen is the total load W_0 (in thousand pounds) on the steel pistons required to bulge the nickel-steel jacket by the amounts entered under the various columns. The second row gives the pressure-intensity $P_0 = W_0/\pi b_0^2$ in thousand pounds per square inch exerted on the end of the specimen of radius b_0. The third line gives the average pressure-intensity $P = \widehat{zz}$ in thousand pounds per square inch at the central portion of the specimen in the direction of the axis, correcting for the effect of the bulge from formula (20). It will be noticed that the average longitudinal pressure at the center is somewhat less than that over the ends by amounts which increase considerably with the harder rocks. The final results given in Tables I and II are shown graphically in Plates I and II, respectively. Against the lateral pressures (given by the experiment on tallow) are plotted the longitudinal pressures required to bulge the nickel-steel jacket to the same extent. For such of the rocks as give curves approximating to straight lines we may say that a definite *modulus of plasticity* and *coefficient of internal friction* exist. Rough estimates of these constants as determined for the soft rocks from large-scale curves are given in Table III, in which the first entry corresponds to the 0.25-centimeter wall nickel-steel jacket and the second to the 0.33-centimeter wall.* It will be noticed that the two sets of results are in poor agreement for K, and are only in rough agreement for μ, the difficulty arising from attempting to fit a straight line to a series of points which are only approximately colinear.

In the case of the harder rocks no definite coefficient of friction can be said to exist. In the case of dolomite and Belgian black marble it is noticed that the coefficient of friction tends to diminish with increasing longitudinal and lateral stress. Slate gives a very irregular curve due to the development of cracks while the material is stressed. The sudden bend in the curves for diabase and granite is attributed to the actual breakdown of the rock material. From the curves of Plates I and II it will be noticed that this occurs in the neighborhood of $\widehat{zz} = 150{,}000$, $\widehat{xx} = 25{,}000$, corresponding to a stress-difference of 125,000 pounds per square inch. In a general way this result confirms the conclusion already arrived at from a discussion of the experiments of Adams on the pressure required to close up small cylindrical cavities in specimens of Westerly granite. In the writer's paper already mentioned (p. 641, n. 1) it was pointed out that the stress-difference required to break down the rock material in the neighborhood of small cavities amounted to as much as

TABLE I

0.25-Centimeter Wall		1	2	3	4	5	6	7	8	9	10	11	12
Bulge $2b_0 = 0.7874''$	$2b - 2b_0$	0.002 "	0.004 "	0.006 "	0.008 "	0.010 "	0.020 "	0.030 "	0.040 "	0.050 "	0.060 "	0.080 "	0.100 "
	$2b$	.7894"	.7914"	.7934"	.7954"	.7974"	.8074"	.8174"	.8274"	.8374"	.8474"	.8674"	.8874"
	$1 - b_e^2/b^2$	0.004	0.010	0.014	0.020	0.023	0.048	0.071	0.095	0.115	0.136	0.176	0.213
Tallow	W_0	6.5	8.2	8.8	9.2	9.6	10.8	11.7	12.5	13.0	13.4	14.1	14.7
	$P_0 = \mathfrak{P}$	13.4	16.9	18.1	19.0	19.7	22.2	24.0	25.7	26.7	27.5	29.0	30.3
	$\mathfrak{W} = \mathfrak{P}$	13.4	16.9	18.1	19.0	19.7	22.2	24.0	25.7	26.7	27.5	29.0	30.3
Steatite	W_0	18.0	19.7	20.5	21.3	21.8	24.0	25.6	27.1	28.5	29.8	32.2	34.3
	P_0	36.9	40.4	42.1	43.7	44.7	49.3	52.6	55.6	58.4	61.1	66.1	70.4
	$\mathfrak{W}$	36.8	40.2	41.8	43.2	44.1	48.0	50.5	52.8	54.8	56.5	59.6	61.9
Alabaster	W_0	18.0	22.6	24.0	25.0	26.0	29.5	31.9	33.8	35.3	36.6	39.0	41.0
	P_0	37.0	46.4	49.3	51.3	53.4	60.6	65.4	69.3	72.4	75.1	80.1	84.1
	$\mathfrak{W}$	36.9	46.1	48.9	50.7	52.6	58.7	62.4	65.2	67.2	68.6	71.1	72.7
Sandstone	W_0	24.5	27.0	27.7	28.7	29.5	32.2	34.5	36.5	38.4	40.0	43.0	45.3
	P_0	50.3	55.4	56.9	58.8	60.5	66.0	70.7	74.8	78.7	82.1	88.2	92.9
	$\mathfrak{W}$	50.2	55.0	56.4	58.0	59.5	63.9	67.3	70.2	72.7	74.6	77.8	79.6
Marble	W_0	22.0	26.2	27.5	30.0	31.0	36.2	40.0	43.1	45.2	47.3	51.2	54.7
	P_0	45.1	53.8	56.4	61.6	63.6	74.2	82.0	88.4	92.8	97.0	105.0	112.1
	$\mathfrak{W}$	45.0	53.5	55.9	60.8	62.6	71.7	77.8	82.5	85.2	87.5	91.6	94.7
Dolomite	W_0	35.0	38.0	43.0	44.2	45.5	49.2	51.7	53.7	55.4	56.9	59.7	62.5
	P_0	71.8	78.0	88.2	90.8	93.3	101.0	106.0	110.1	113.6	116.6	122.4	128.2
	$\mathfrak{W}$	71.6	77.4	87.3	89.3	91.6	97.2	100.1	102.1	103.6	104.5	105.9	107.4
Belgian black marble	W_0	41.0	48.0	49.5	50.6	51.6	54.6	56.8	58.7	60.4	61.9	64.8	67.2
	P_0	84.1	98.4	101.5	103.7	105.8	112.0	116.5	120.4	123.9	127.0	132.9	137.9
	$\mathfrak{W}$	83.9	97.6	100.3	101.9	103.7	107.6	109.8	111.5	112.7	113.4	11.46	115.0
Slate	W_0	(53.0)	(56.4)	(56.7)	(56.9)	58.8	62.4	62.8	63.6	64.5	65.4	67.0	69.0
	P_0	(108.7)	(115.7)	(116.3)	(116.7)	120.6	128.0	128.8	130.2	132.3	134.1	137.4	141.5
	$\mathfrak{W}$	(108.3)	(114.7)	(114.9)	(114.7)	118.2	122.8	121.1	120.3	120.2	119.5	118.2	117.8
Diabase	W_0	46.0	54.0	58.5	60.7	63.5	68.9	71.5	73.3	74.5	75.5	77.7	79.7
	P_0	94.3	110.8	120.0	124.5	130.2	141.2	146.6	150.3	152.8	154.8	159.3	163.4
	$\mathfrak{W}$	94.0	109.9	118.6	122.3	127.5	135.4	137.7	138.5	138.3	137.4	136.3	135.0
Granite	W_0	57.0	69.0	74.0	76.5	77.4	79.0	79.2	79.7	80.5	81.6	84.1	86.6
	P_0	116.9	142.0	151.8	156.9	158.7	159.7	162.4	163.4	165.1	167.3	172.5	177.6
	$\mathfrak{W}$	116.6	140.6	149.9	154.0	155.4	153.0	152.4	150.4	149.2	148.2	147.2	146.3
Lead	W_0	7.0	9.1	9.6	10.1	10.4	11.7	12.6	13.3	13.8	14.3	14.9	15.4
	P_0	14.4	18.7	19.7	20.8	21.4	24.0	25.9	27.3	28.3	29.4	30.6	31.9
	$\mathfrak{W}$	14.4	18.7	19.7	20.7	21.4	23.9	25.7	27.2	28.1	29.2	30.3	31.4

TABLE II

TABLE II

0.33-CENTIMETER WALL		1	2	3	4	5	6	7	8	9	10	11	12
Bulge $2b_0 = 0.7874''$	$2b - 2b_0$	0.002 "	0.004 "	0.006 "	0.008 "	0.010 "	0.020 "	0.030 "	0.040 "	0.050 "	0.060 "	0.080 "	0.100 "
	$2b$	.7894"	.7914"	.7934"	.7954"	.7974"	.8074"	.8174"	.8274"	.8374"	.8474"	.8674"	.8874"
	$1 - b_e^2/b^2$	0.004	0.010	0.014	0.020	0.023	0.048	0.071	0.095	0.115	0.136	0.176	0.213
Tallow	W_e	10.2	11.4	12.1	12.6	13.0	14.7	16.2	17.3	18.2	18.7	19.8	20.5
	$P_e = f_2$	20.9	23.4	24.9	25.9	26.7	30.3	33.3	35.5	37.4	38.4	40.6	42.1
	$f_2 = f_2$	20.9	23.4	24.9	25.9	26.7	30.3	33.3	35.5	37.4	38.4	40.6	42.1
Steatite	W_e	19.0	24.2	25.5	26.5	27.5	30.9	34.0	36.7	39.0	41.0	44.2	46.8
	P_e	39.0	49.6	52.3	54.3	56.4	63.3	69.7	75.2	80.0	84.0	90.7	95.9
	f_2	38.9	49.3	51.9	53.7	55.6	61.7	67.1	71.5	75.1	77.7	81.8	84.4
Alabaster	W_e	24.0	28.5	30.75	32.3	33.5	37.5	40.7	43.2	45.2	47.0	49.7	52.2
	P_e	49.2	58.4	63.0	66.2	68.7	76.9	83.4	88.6	92.7	96.4	101.9	107.0
	f_2	49.1	58.0	62.4	65.4	67.6	74.6	79.8	83.6	86.3	88.4	91.0	93.2
Sandstone	W_e	32.5	33.5	35.0	35.7	36.7	40.5	44.1	47.1	50.1	52.5	57.2	61.0
	P_e	66.6	68.7	71.8	73.3	75.2	83.0	90.4	96.6	102.7	10.76	117.3	125.0
	f_2	66.4	68.2	71.1	72.3	74.0	80.4	86.3	90.8	95.2	98.0	103.7	107.4
Marble	W_e	26.0	31.0	33.7	35.0	37.5	43.5	48.2	52.5	54.5	57.2	63.4	66.7
	P_e	53.3	63.6	69.1	71.8	76.9	89.2	98.8	105.6	111.7	117.3	127.9	136.7
	f_2	53.2	63.2	68.4	70.9	75.7	86.3	94.1	98.9	103.1	106.5	112.4	116.5
Dolomite	W_e	42.0	47.0	49.5	51.5	53.0	57.8	61.0	63.8	66.1	68.3	72.7	76.5
	P_e	86.1	96.4	101.5	105.6	108.7	118.5	125.0	130.8	135.6	140.0	149.2	156.9
	f_2	85.9	95.6	100.3	104.0	106.7	114.3	118.4	121.7	124.3	126.0	130.1	132.4
Belgian black marble	W_e	46.5	52.5	54.5	55.7	56.5	60.1	62.9	65.4	67.8	70.0	74.1	77.8
	P_e	95.3	107.0	111.8	114.2	115.9	123.3	129.0	134.1	139.0	143.6	152.0	159.5
	f_2	95.0	106.7	110.5	112.2	113.7	118.8	122.1	124.8	127.3	129.1	132.3	134.5
Slate	W_e	60.0	69.0	75.0	(75.3)	(75.5)	76.7	79.0	80.2	80.8	81.8	84.7	87.4
	P_e	123.1	141.7	154.0	(155.0)	(255.4)	157.9	162.6	164.8	166.8	168.4	174.4	179.6
	f_2	122.6	140.4	152.1	(152.4)	(152.1)	151.7	153.3	152.5	152.0	150.5	150.7	150.3
Diabase	W_e	55.0	62.0	69.0	73.0	75.5	82.2	85.0	86.7	88.3	89.9	93.0	96.2
	P_e	114.0	127.4	141.8	150.0	155.1	168.9	175.0	178.2	181.4	184.7	191.1	197.7
	f_2	113.6	126.3	140.1	147.5	152.0	162.2	164.8	164.7	164.9	164.7	164.6	164.6
Granite	W_e	(60.0)	76.0	80.2	83.2	85.1	89.5	92.0	94.0	96.0	97.8	101.2	104.3
	P_e	(123.1)	156.2	165.2	171.0	174.8	183.9	189.1	193.2	197.3	200.9	207.6	213.8
	f_2	(122.6)	154.8	163.1	168.1	171.2	176.4	177.9	178.2	178.9	178.6	178.1	177.2
Lead	W_e	10.0	12.0	12.5	13.0	13.7	15.4	16.8	17.8	18.7	19.3	20.0	20.8
	P_e	20.5	24.6	25.7	26.7	28.1	31.6	34.5	36.5	38.4	39.6	41.1	42.7
	f_2	20.5	24.5	25.6	26.7	28.0	31.5	34.4	36.4	38.3	39.4	41.0	42.7

160,000–200,000 pounds per square inch. The conclusion, there limited to small cavities, is extended by the present experiments of Adams and Bancroft to continuous rock stressed under conditions approaching those existing in

TABLE III

Specimen	K	μ
	(Pounds per square inch)	
Steatite.....	5,500–1,800	0.24–0.32
Alabaster.....	4,200–3,100	0.37–0.38
Sandstone.....	7,500–3,100	0.34–0.40
Marble.....	850–1,500	0.58–0.52
Lead.....	850– 500	0.00

the earth's interior, in which circumstances a limiting stress-difference several times greater than that obtained by the usual crushing test must be employed.

NOTE ON THE DEPOSITS CONTAINING HUMAN REMAINS AND ARTIFACTS AT VERO, FLORIDA

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The deposits containing human remains and artifacts at Vero, Florida, have been described in the issue of the *Journal of Geology* of January–February, 1917.[1] Among interpretations advanced in connection with that discussion, that proposed by Dr. R. T. Chamberlin differed in one important respect from that offered by the writer. To Dr. Chamberlin it seemed that the fossils found in the stream bed, or most of them, were secondary, having been washed in from a near-by older formation, while the writer held that these fossils were primary. In order, if possible, to harmonize these views, Dr. Chamberlin very considerately returned to Florida for the purpose of re-examining the deposits and was present with the writer at Vero from March 16 to March 20, 1917. Professor E. W. Berry, who is engaged in a study of the fossil plants, was also present, as well as Mr. H. Gunter and Mr. Isaac M. Weills. The additional collections made include potsherds, bone implements, flints, vertebrate and plant fossils.

The banks of both the main and the lateral canals were reexamined, and it was found that the upland formation from which Dr. Chamberlin assumed that the vertebrate fossils had washed was almost if not entirely non-fossiliferous. These new observations have served to define more closely the problems to be solved. It is evident that the fossils found at this locality are primary fossils in the stream bed and were not washed in from the older formation of the uplands near by. It is quite obvious also, both on old and on new evidence, and in conformity with views previously expressed, that the human remains and artifacts of this deposit do not represent burials by human agency as was maintained by Dr. Hrdlička in the former discussion. The stratigraphic evidence on this point is so conclusive that it is certain that the hypothesis of burial by human agency may be eliminated

[1] "Symposium on the Age and Relations of the Fossil Human Remains Found at Vero, Florida," XXV (1917), 1–62.

as a possibility. It thus appears that the problem is confined to a study of the stream fill, and that the determination of the age of the human remains depends upon a correct understanding of the history of accumulation of material within the stream bed.

The view which the writer holds regarding the stream deposit has been expressed in papers previously published. The earliest phase of deposition in this stream bed includes local accumulations of muck which fill holes and channels in the underlying marine shell marl. Another phase which is general and is observed throughout most of the stream valley includes light-colored, often cross-bedded, sands which pass at a higher level into brown or dark-colored sand. This part of the deposit has been designated as stratum No. 2. Above this brown sand is found as a rule an accumulation of alternating layers of sand and muck, stratum No. 3, which when fully developed is capped by a fresh-water marl. The maximum thickness of the stream fill as preserved at the present time is from 4 to 8 feet. The first human bones obtained were in the brown sand beneath the fresh-water marl, and additional bones were subsequently found in this sand. A flint spawl was found in place in the sand and additional flints and two bone implements were obtained from siftings. From the alternating layers of sand and muck which lie above the brown sand human bones and artifacts have been taken in considerable numbers.

As already stated, human bones and implements have been taken from beneath the fresh-water marl. The last bone implement collected on the recent visit to the locality (Florida Survey collection No. 7786) was found beneath this marl and lay at a depth of 4 feet from the surface. The place of this implement is on the south bank 32 feet west of the lateral inlet canal. The bank at this place is relatively high and has retained its capping of fresh-water marl. It is evident, therefore, that the human materials of this deposit were not accumulated by the recent stream. On the contrary, they lie in deposits accumulated at an earlier stage.

The writer's interpretation, as expressed in papers previously published, is that the human remains and artifacts are contemporaneous with the extinct vertebrates of this deposit, and that the age of the formation, according to the accepted interpretation of faunas and floras, is Pleistocene.

THE FOSSIL PLANTS FROM VERO, FLORIDA

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The discovery of human remains associated with an extinct mammalian fauna at Vero, Florida, has excited a great deal of local and general interest, and various theories regarding the age of these remains and the manner of their occurrence have already been advanced, and admirable accounts of the local geology have been given by Sellards and others.[1] It is therefore unnecessary for me to repeat any of these details in connection with the present preliminary abstract of my study of the fossil plants.

Plant remains in the form of laminae of impure peat or scattered fruits, chiefly acorns, are present from the bottom to the top of the deposits overlying the shell marl which forms the base of the section. The lower sands (designated No. 2 by Sellards) have yielded no leaves and but few acorns, but the upper bed (Sellards, No. 3) contains many leaf layers alternating with sand laminae, and it is from the latter horizon that all of the plants enumerated in the following pages have been collected, with the exception of one species of acorn which is common to both beds.

Recent and extinct mammalian and other bones occur in both layers, and human remains are also found in both beds. After a thorough study of the local sections and the paleontologic evidence I am convinced that there is no hiatus between beds Nos. 2 and 3 and that there is no great difference in age from the bottom to the top of the section, although it records changing physical conditions and necessarily becomes gradually more and more recent as the top of the section is approached. The lower sand marks the recession of the sea in which the underlying shell marl was formed. The

[1] E. H. Sellards, *Am. Jour. Sci.* (IV), XLII (1916), 1–18; *Eighth Ann. Rept. Florida Geol. Surv.*, 1916, pp. 122–60, Pls. 15–31; *Science*, N.S., XLIV (1916), 615–17; *Jour. Geol.*, XXV (1917), 4–24, Figs. 1–4; R. T. Chamberlin, *ibid.*, XXV (1917), 25–39, Figs. 1–9; T. W. Vaughan, *ibid.*, pp. 40–42; A. Hrdlička, *ibid.*, pp. 43–51, Figs. 1, 2; O. P. Hay, *ibid.*, pp. 52–55; G. G. MacCurdy, *ibid.*, pp. 56–62, Figs. 1–6.

upper beds (No. 3) mark successive seasonal layers of valley filling in the narrow valley of a small stream. This stream was apparently always small, and the marvelous abundance of fossils at this one point seems to be due to a bar or sinkhole or similar cache formed near the junction of the two lateral branches which united near this point to form the main stream. The determinable plants are represented almost exclusively by fruits or seeds, as the leaves, with the exception of the coriaceous oaks, which are abundant, were too thoroughly decayed before they were buried to retain their identity.

The study of such remains is beset with many difficulties. The material has to be sorted without allowing it to dry. It then has to be impregnated with paraffin simultaneous with drying. Finally, identification is hampered by the lack of recent material for comparison, and when the material is identified the determination of the exact range of the still existing species on which so much hinges is a matter of great uncertainty in the present state of our knowledge of plant geography. I am under obligations to, and take this opportunity of thanking, Mr. W. L. McAtee, of the Biological Survey, for determining five species of fruits for me.

The following plant species have been identified from the Vero deposits:

Pinus taeda Linné
Pinus caribaea Morelet
Pinus sp.
Taxodium distichum (Linné) Rich.
Carex sp.
Pistia spathulata Michx.
Seronoa serrulata (Michx.) Hooker
Sabal palmetto (Walt.) R. & S.
Myrica cerifera Linné
Leitneria floridana Chapman (?)
Quercus virginiana Mill.
Quercus Laurifolia Michx.
Quercus Chapmani Sargent (?)
Quercus brevifolia (Lam.) Sargent
Polygonum sp.
Magnolia virginiana Linné
Anona glabra Linné
Brasenia purpurea (Michx.) Caspary
Ilex glabra (Linné) A. Gray
Acer rubrum Linné
Zizyphus sp. (new species)
Vitis cf. rotundifolia Michx.
Vitis sp.
Benzoin cf. melissaefolium (Walt.) Nees
Viburnum nudum Linné
Viburnum cf. dentatum Linné
Xanthium sp.

The most abundant form in the preceding list is *Quercus laurifolia*, which is represented in the upper beds by leaves, cupules, and acorns and in the lower beds by cupules and acorns. It is still

found growing in the Vero region, but is not nearly so abundant as far south as Vero at the present time as it appears to have been at the time the Vero deposits were laid down.

SUMMARY

The foregoing comprise more or less positively identified remains of twenty-seven species of plants. Nineteen of these have not been previously found fossil, while the following eight have already been discovered in Pliocene or Pleistocene deposits:

Pinus taeda	Brasenia purpurea
Taxodium distichum	Acer rubrum
Quercus virginiana	Zizyphus sp.
Magnolia virginiana	Viburnum nudum

The problem in so far as it relates to the evidence of the plants depends on the correct evaluation of the change which this plant assemblage shows when compared with the flora now growing at Vero.

Of the plants found fossil the following are still found at Vero, and I have included in this list as probably found in the present flora of Vero the four forms of *Pinus*, *Carex*, *Polygonum*, and *Xanthium* which are not specifically identified. This list comprises:

Pinus caribaea	Quercus brevifolia
Pinus sp.	Polygonum sp.
Carex sp.	Magnolia virginiana
Serenoa serrulata	Ilex glabra
Sabal palmetto	Acer rubrum
Myrica cerifera	Vitis cf. rotundifolia
Quercus virginiana	Xanthium sp.
Quercus laurifolia	

In addition to the foregoing fifteen species still found at Vero the following two species are found growing within ten or twelve miles of Vero:

Taxodium distichum	Anona glabra

Three species approach to within about fifty miles of Vero, being recorded from the southern extension of the lake region flora of the central peninsula in De Soto County. These are:

Pinus taeda	Viburnum nudum
Pistia spathulata	

The following six species are not now found growing in peninsular Florida:

Leitneria floridana (?)	Vitis sp.
Quercus chapmani (?)	Benzoin cf. melissaefolium
Brasenia purpurea	Viburnum cf. dentatum

Of these *Leitneria floridana* is a very local form not found nearer than the Apalachicola River, and the chief center of growth of *Quercus chapmani* is also in west Florida, while the true *Viburnum dentatum* does not occur nearer than the upland region of Georgia.

Finally, the Vero deposits have yielded a fruit probably identical with similar remains from the late Pleistocene of New Jersey representing an entirely extinct species of *Zizyphus*, a genus abundant in Southeastern North America during the Tertiary, but not now represented except by a single species of the arid southwest (Texas to Arizona).

Two of the fossil species have been recorded from the Pliocene. These are *Taxodium distichum* and *Magnolia virginiana*. One, *Quercus virginiana*, is found in the early Pleistocene of both Kentucky and Alabama, and the following occur in the late Pleistocene:

Pinus taeda	Acer rubrum
Taxodium distichum	Zizyphus sp.
Quercus virginiana	Viburnum nudum
Brasenia purpurea	

These latter, while they constitute but 26 per cent of the known fossil flora at Vero, are especially significant in connection with the fact that they all occur elsewhere in the physiographically youngest of the Pleistocene terrace deposits, namely, the Talbot of New Jersey and Maryland, the Chowan of North Carolina, and the corresponding lowest terrace at several localities in Alabama, while the Vero deposits constitute the youngest physiographic terrace plain of the region and are referred to the Pensacola terrace by Matson.[1]

In my judgment and in the ordinary acceptance of that term this flora is unquestionably of late Pleistocene age.

[1] G. C. Matson, *U.S. Geol. Surv., Water Supply Paper 319*, 1913, pp. 31–35.

Regarding its bearing on the interesting problem of the age of the human and associated mammalian and other remains at Vero, my study of the locality furnishes the following somewhat categorical conclusions. The underlying shell marl which forms a definite and undisputed datum plane is late Pleistocene in age. Its species all exist in near-by waters at the present time, and many of them have been recorded from shell marls found from southern New Jersey to the Florida keys and forming a part of the lowest and latest well-defined terrace plain previously mentioned as having been named Talbot in Maryland, Chowan in North Carolina, and Pensacola in Florida. It follows that the vertebrate remains which are so numerous at Vero cannot possibly be of Middle or early Pleistocene age unless they are regarded as having been reworked from older deposits, and I cannot conceive that this was possible, nor do the vertebrate paleontologists who have examined the deposits consider that such was the case. In fact, I believe that, if it had not been for the overestimate of the age of this vertebrate fauna, Dr. Chamberlin would not have advanced his hypothesis of the reworking and mechanical mixing of these bones and Dr. Hrdlička would not have insisted on the human burial theory to account for the presence of the human skeletal remains. Nothing is more reasonable than to suppose that the larger elements in the Middle Pleistocene fauna of more northern areas should have lingered for thousands of years in this more genial southern clime until the presence of man in considerable numbers and the changing climate as is attested by the fossil plants should have brought about the extinction of a large percentage of the fauna. The fauna itself confirms the rather limited data furnished by the fossil flora of this change in climate, since it indicates a more mesophytic habitat than exists today in the vicinity of Vero. Regarding the burial theory of Dr. Hrdlička it may be said that a part of the plant material came from immediately above one of the human skeletons, and I cannot conceive of the possibility of not being able to see evidence of artificial burial in material made up of alternate layers of sand and matted leaves and other vegetable débris. I therefore see no reason to doubt that relative modern men were contemporaneous with this partially extinct fauna of Middle Pleistocene

aspect which survived in Florida to the late Pleistocene. With regard to the exact age of the Vero deposits there are, it seems to me, but two alternatives, and these apply equally and are in large part derived from a study of the physiography and the faunas and floras of the corresponding topographic forms in the other states of the Coastal Plain. These alternatives are that they are about the same age as the Peorian interglacial deposits of the Mississippi Valley or are immediately post-Wisconsin and correspond with what the Scandinavian geologists have named Litorina time.

FURTHER STUDIES AT VERO, FLORIDA

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In a recent number of this *Journal* there appeared a symposium on the age and relations of fossil human remains found near Vero, Florida.[1] The several investigators attacked the problem from quite different viewpoints and developed considerable difference of opinion. Later Dr. Sellards planned to spend an additional week at Vero with Dr. E. W. Berry in further study of the critical points involved in the case. He was good enough to invite the writer to join in this further inquiry, and this invitation was cordially accepted. As a result of the wider examination of essential points made possible by my second visit, I desire to amend and extend the interpretation of the history of the human bones and associated relics previously offered.

My studies on the first visit were given almost wholly to an endeavor to work out the physical history and time relations of the formations at Vero, as this was regarded as a step necessary to the safe interpretation of the relics embraced in them. This seemed especially necessary because the dates of the appearance of man and of the disappearance of the extinct animals were among the very points brought into question and could not themselves be used as decisive criteria. On the other hand, the nature and successions of the formations afford some of the most critical evidence bearing on these dates. It will perhaps be recalled that the history of the formations was found to be rather definitely deployed, and that the time relations of the deposits were quite well indicated by the physical criteria available, irrespective of their fossil contents. My former reading of this history was confirmed in all essential

[1] E. H. Sellards, R. T. Chamberlin, T. W. Vaughan, Aleš Hrdlička, O. P. Hay, and G. G. MacCurdy, "Symposium on the Age and Relations of the Fossil Human Remains Found at Vero, Florida," *Jour. Geol.*, XXV (1917), 1–62.

particulars by what was seen during the second visit. Its essentials are here recalled for the sake of the discussion following.

1. During a submergence of this portion of the east coast of Florida there was laid down a striking marine shell marl which has sometimes been called "coquina." It is the oldest formation exposed to view and has been referred without question to the Pleistocene. Though its precise place within the Pleistocene has not been determined, its fauna was essentially the same as that now living in the adjacent ocean. Following the deposition of the marine shell marl, a withdrawal of the sea gradually brought this region into the horizon of terrestrial action. In the transition, beach conditions prevailed, resulting in sandy deposits, partly marine, partly terrestrial.

2. At the appropriate stage in the withdrawal of the sea a barrier ridge was developed immediately to the west of the present location of the Florida East Coast Railway. This ridge parallels the railroad and the coast for many miles both north and south of Vero, and throughout most of its extent it is a pronounced topographic feature. West of it was a marshy area.

3. With further withdrawal of the sea a newer barrier ridge developed from two to two and one-half miles east of the earlier Vero beach ridge. This constitutes the present east coast of Florida. For over one hundred miles it incloses, between itself and the mainland, a salt-water lagoon, known as the Indian River.

4. After the withdrawal of the sea from the Vero beach ridge, erosion developed a channel in essentially the position now occupied by Van Valkenburg's Creek. The very low gradient and notable width of this channel in proportion to its very insignificant depth, which was limited by sea-level, suggest that erosion, which here was slow at the best, was in progress for a considerable time.

5. In the marshy region west of the Vero beach ridge bog deposits accumulated here and there. Cementation had also affected certain horizons of the sands of this tract and had converted them into a sandstone. This had been effected by the deposition of iron and manganese oxides as well as organic matter in the sands. The length of time involved in this process of conver-

sion of the sands into sandstone may well have been considerable, though it cannot be definitely measured.

6. But, whatever the length of this period, it is important to observe that *the filling of the channel of the creek* did not begin until *after the sand had been converted into black sandstone*, for water-worn pebbles of this black sandstone *are abundant in the basal portion of*

FIG. 1.—The present channel of Van Valkenburg's Creek, dry since the construction of the drainage canal in 1913. Shows the relatively slight depth of the channel.

the channel fill. They are in fact rather more conspicuous at the base of the fill than at higher levels, although occurring throughout. The special significance of these black pebbles, as brought out in the symposium, lies in the fact that they fix the date of the filling of the channel with respect to the old bog area to the west. The oldest fill in the creek channel is notably younger than the bog deposits of the uplands back of the main beach ridge.

7. The filling of the creek channel from this beginning up to the present has taken place in two stages, which appear to be quite

distinct in some portions of the channel, but which at some other points can be separated only with much doubt. At best they are thin, both of them together averaging only 5–7 feet in thickness, and they are quite changeable in composition. The lower of these has been designated formation No. 2 by Sellards and the upper one formation No. 3. In this paper the former will be termed the lower creek deposit and the latter the upper creek deposit. The bones and relics in question were found in these two creek deposits.

The discrimination of these successive stages of formation made it seem quite possible that the land life of the times began to occupy this region during the stages of emergence, and hence that bones of the extinct mammals and other vertebrates might have accumulated in the marshy area to the west of the Vero beach ridge in Pleistocene times, following not long after the coquina stage, and that later, as Van Valkenburg's Creek gradually cut back into this area, these old Pleistocene bones were washed into the stream channel and concentrated in the creek deposit, while at this later time there mingled with them relics of the more recent vertebrates and plants, as well as human remains.[1] Thus the deposit of the stream channel might contain fossils of quite different ages in intimate association. The geologic conditions and the sequence of events seemed such as to suggest and to support this hypothesis.

On the assumption that the extinct mammals were perhaps as old as Middle Pleistocene—as was then urged—and that the coquina formation which underlies the region could not well be interpreted as much older than this—if indeed as old, since all of its fossils belong to living species—there seemed to be rather urgent reasons for presuming that at least the older of the extinct mammals invaded the region as soon after its emergence from the sea as conditions permitted. They were therefore supposed to have been present during the formation of the marsh deposit back of the beach ridge, and to have, in all probability, been buried in it, and their relics derived from it in the subsequent trenching and filling by Van Valkenburg's Creek. The finding of balls of black sandstone from the marsh deposit in both the older and the younger creek deposits seemed to fit at once, and help explain, this very

[1] Symposium, pp. 25–39.

puzzling combination of bones of extinct animals of supposedly Middle Pleistocene age mingled with fragments of human pottery of almost obvious recency.

The actual presence of bones of the extinct animals in this Pleistocene marshy area was not observed, for, on the first visit, time did not permit an adequate examination. And so a leading

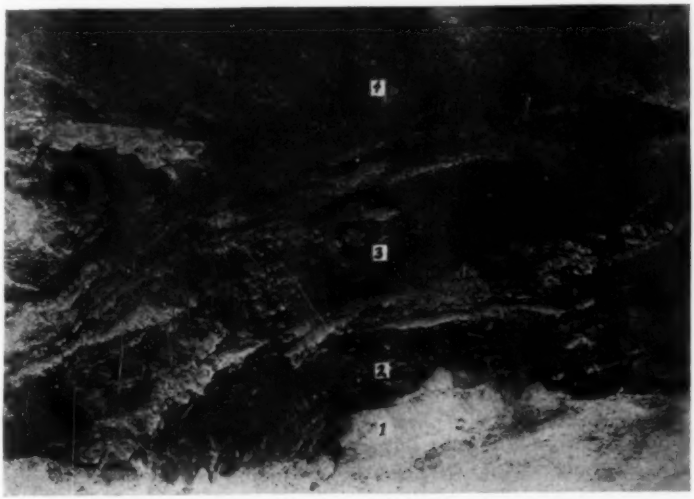

FIG. 2.—The formations of the creek section exposed by digging into the south bank of the canal near point marked *N* in Fig. 4. No. 1 represents the marine shell marl (coquina) grading upward into light-colored sands; No. 2 is the lower creek filling of variously stained sands (Sellards' formation No. 2); No. 3 represents the upper creek filling (Sellards' formation No. 3), consisting of alternate layers and lenses of sand and muck; No. 4 is the loose dump material piled on the surface in excavating the canal.

purpose of the second visit was to search the older upland formations for direct fossil evidence on this point. This search was not successful in finding bones of the extinct animals, either *in situ*, or in the canal dump from the upland area through which the two forks of the creek have cut. The conditions that prevailed at the time of the marsh deposit to the west of the barrier ridge seem to have been inhospitable to life of the types of the extinct animals

in question, or else the nature of the formation was unfavorable to their preservation. This, of course, is not conclusive evidence that they did not then live in the region, but it greatly weakens the hypothesis that bones deposited in these beds were sources of supply to the creek deposit after the analogy of the black pebbles.

Bones as well as coarser fragments of any durable material should, of course, tend to become concentrated in a stream bed as the finer inclosing sands are washed downstream. This is a well-recognized principle and it might well account for the fact that bone fragments are rare in the upland formations and numerous in the creek channel deposits. But whether this selective concentration of coarser fragments in the channel by the action of the stream is quantitatively adequate to explain the difference is questionable, and it is not wise to appeal to it unless all other explanations fail. The solution of the riddle of the mixture of the bones of extinct animals with human bones and pottery was therefore sought on other lines.

It is true that, at a point three miles west of Vero, Dr. Sellards had found the wreck of a proboscidian in a fresh-water marl deposit close to the surface and referable to the general upland deposit back of the beach ridge.[1] Dr. Sellards had also recognized a fauna similar to that found in his formation No. 2—the lower creek deposit—in a fresh-water marl bed belonging to the upland deposit at a point about 1,700 feet east of the Florida East Coast Railway bridge, i.e., *downstream* from the deposits which contain human relics. Both these facts seem to imply that a fauna of the general type found in the lower creek deposit occupied the region at some time during the formation of the upland deposits, and to this extent they support the general correctness of the inferences entertained in my contribution to the symposium, but they do not support the specific view that the bones of the lower creek deposit were in any large measure derived from the lagoon, or marsh, deposit of which the indurated black sand is a part.

These facts also weaken the presumption that the relics of the extinct animals really imply so great age as Middle Pleistocene. Dr. Hay, who favored the view that they were closely related to

[1] Symposium, p. 55.

the fauna of the Aftonian inter-glacial beds of Iowa, yet recognized that "this fauna might have continued on for another stage or two, but by the time of the Illinoian drift it had become essentially modified."[1] It is further to be recognized as not improbable that this fauna may have lingered longer at the south than it did at the north, where the advances and retreats of the ice border were putting the fauna under the stress of an oscillating climate.

The marine coquina deposit, which lies below all the upland beds and the creek deposits as well, does not bear evidence of great age, its shells being all of living species. This deposit, or perhaps more strictly the beach sands into which it grades upward, are referred by the geologists of this and adjoining states to what has been termed the third or lowest Pleistocene marine terrace formation. The age of this terrace was assigned by Matson to late Pleistocene.[2]

There are good reasons, therefore, in the stratigraphy and the topographical aspects of the deposits at Vero, for regarding the extinct mammals and other vertebrates as continuing to a relatively late date. The aspects of the problem thus developed made a closer scrutiny of the two creek deposits more imperative, for, as we have seen, both of these deposits were late in the history of the formations of the region, and the oldest of these formations bears both a paleontological and a topographical aspect of relative recency.

This closer scrutiny at the time of the second visit developed evidence both for and against the point previously made by Dr. Sellards that the delicate condition of the fossils—as well as their grouping—was not consistent with the view that they were derived from an older formation by stream action. Dr. Sellards put forward an increasing number of fossil remains which, on account of their fragile nature, or because of the close association of various bones, he did not believe could have suffered transportation or much disturbance since fossilization. That an occasional specimen of this sort need not be of much significance was pretty effectually established by the finding, among a half-dozen fragile

[1] Symposium, pp. 54–55.

[2] *Ibid.*, p. 40; G. E. Matson, "Geology and Ground Waters of Florida," *U.S. Geol. Surv., Water Supply Paper 319*, 1913, pp. 31–35.

carapaces of turtles, of one specimen still firmly holding together and undoubtedly still capable of being swept along by a stream for a considerable distance without being torn to pieces. But the cumulative evidence of the cases presented suggested strongly that various particular individuals, at least, were primary fossils but little disturbed since entombment.

On the whole, it seems to me that Dr. Sellards has strengthened his view that at least an essential part of the fossils of the lower creek deposit are primary to that deposit, and that the extinct animals represented by these fossils were denizens of the region as late as the formation of the lower creek deposit, Sellards' formation No. 2. This does not entirely dispose of the hypothesis that some of them were washed in from the older deposits in the process of stream-cutting and stream-filling, but it renders that possibility less vital to the essential question—the time of man's appearance in this region. At the same time, of course, it brings the time of extinction of the fauna of the lower creek deposit down to a relatively recent date.

It, however, left the critical feature of the problem—the admixture of extinct animals with human remains, pottery, and bone implements of modern aspect—still crying for a satisfactory explanation. The crux of the whole problem seemed to be thrown upon the trustworthiness of the discrimination between the upper and the lower creek deposits. Now these upper and lower deposits altogether measure only about 6 feet in thickness on the average. This is a pretty thin deposit to divide into two distinct ages when the natural irregularity of such deposits is considered, and when the composition of the earlier and the later deposits is so nearly the same as it is in this case. The upper creek deposition reaches down to the year 1913, when the digging of the drainage canal put an end to the activity of this portion of Van Valkenburg's Creek, and thus the occurrence within it of pottery, bone implements, and the remains of man is altogether what one might expect. But the presence of these same relics in the lower creek deposit would tell a different story. It therefore becomes imperative to note sharply in just what portions of the creek filling the significant relics were found. It is also equally important to determine critically in what

horizons within the creek deposits the undisturbed individuals of the extinct vertebrates occur. Creek deposits, by their very nature, imply changing conditions from time to time.

Dr. Sellards had appealed to, as evidence against the secondary nature of the fossils of the old vertebrates, a number of bone assemblages, such as a tapir skull, a wolf's head, an armadillo,

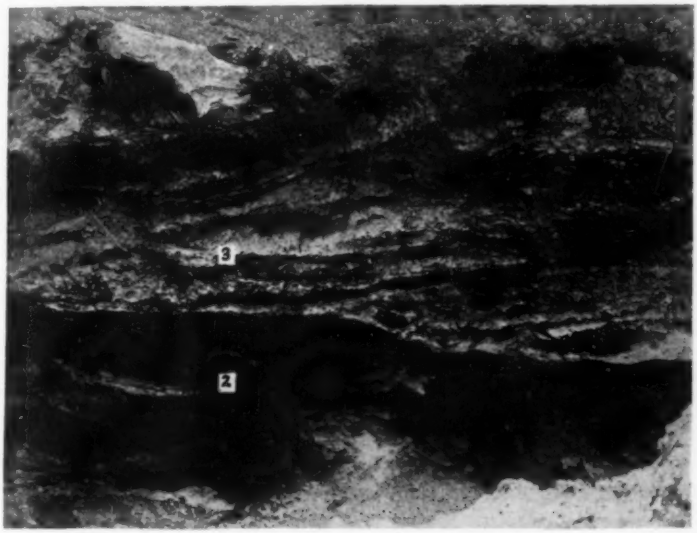

FIG. 3.—View showing a distinct dividing line between the lower creek filling (No. 2) and the upper creek filling (No. 3). Lenses and irregular patches of material in both formations rapidly pinch out, showing considerable scour and fill. Location close to that of Fig. 2, but at a different stage in the progress of the exploratory digging in March, 1917. At the base is the underlying formation No. 1; at the top is the canal dump piled on the surface. Note the thinness of the creek fillings.

turtle carapaces, etc., which he did not believe could have been moved since fossilization. In going over the list one by one with Dr. Sellards, it developed that the fossils of old extinct forms which seemed to him to necessitate the belief that they have not been rewashed, were found in formation No. 2 (the lower creek deposit) and in general rather well down in it. Here must perhaps be

excepted the turtles, but the finding of one very firm carapace near the junction of the two deposits would seem to throw much doubt upon arguments based upon the turtles. If it be admitted, then, that such of these fossils as cannot readily have been transported from elsewhere since fossilization are primary to the lower creek deposit, that would mean that this earlier creek filling is of the same age as these particular types, and so its age is determinable from these types provided they afford decisive evidence. But a development of scarcely less significance in the ultimate interpretation was the bringing out of this very fact that the undisturbed specimens of extinct vertebrates were taken wholly, or chiefly, from the lower creek deposit.

On the other hand, according to the published accounts of Dr. Sellards, the bones of the extinct vertebrates found in the upper creek deposit are much scattered, commonly a few teeth, or a lower jaw, or fragments of one or two other bones.[1] In this condition they do not seem to the writer to preclude more or less reworking by the creek, but rather to imply it.

Next let us consider the location of the human bones and artifacts. On the north bank of the canal the human relics thus far found have come exclusively from the upper creek deposit. No evidence of the presence of man has yet been discovered in the lower creek deposit on the north bank of the canal. At the same time it strikes the writer as an observation equally to be emphasized that the two creek deposits are quite distinct from one another throughout this section along the north bank of the canal. In this section the observer feels little hesitation in drawing the dividing line, and different investigators readily place it at the same level. It can scarcely be without significance that the human relics found thus far in the north bank of the canal all lie *above* this well-marked dividing line, while the vertebrates of greatest age, and those which present the best basis for the claim that they cannot have been rewashed, lie *below* this line.

All the human relics reported to have come from the *lower* creek filling were found in the *south* bank of the canal, and were

[1] E. H. Sellards, "Human Remains and Associated Fossils from the Pleistocene of Florida," *Eighth Ann. Rept. Florida Geol. Surv.*, 1916, pp. 147–52.

obtained from points marked *M* and *N* on the contour map (Fig. 4). It was at point *M* that the original discovery of human bones was made by Mr. Frank Ayers in October, 1915. But since that time the bank at this point has been cut back five or six feet in further search for bones, so that the exact resting-place of this first find of bones can no longer be viewed. According to the description given by Dr. Sellards, these human remains, or skeleton No. 1 as it

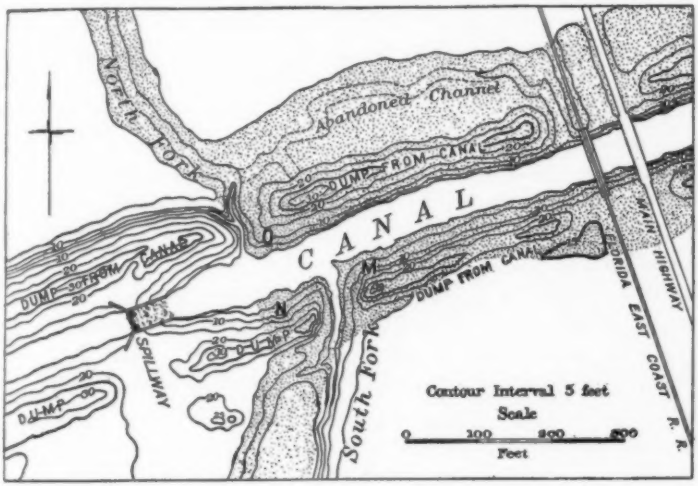

FIG. 4.—Detailed map of the locality where the human bones were found. The canal and the resulting dump piles have done much to change the original topography. The dotted area represents the flood-plain of Van Valkenburg's Creek as it appears to have been just prior to the digging of the canal. The first human skeleton was found at point marked *M*, the second at point marked *N*, while human relics were found also at point *O*. (Reproduced from Symposium, p. 26.)

may be called, were imbedded in brown sand about two feet from the surface of the ground as it existed previous to the construction of the canal.[1] Of these two feet, nine inches, next above the bones, consisted of brown sand, above which lay one foot three inches of sandy, fresh-water marl. All of this was originally assigned to the lower creek fill. If this be correct the upper filling is wanting at

[1] *Op. cit.*, pp. 131–32.

this place. But in his symposium paper Dr. Sellards had come to regard this marl as probably equivalent to formation No. 3 (upper creek fill),[1] and in that article assigned to it a thickness of 18 inches.[2] Only a few inches of brown sand therefore remain as a basis for referring the bones to the lower creek deposit in a case in which the correct reference is a matter of critical importance. The case accordingly does not seem to the present writer to be one that may safely be regarded as conclusive.

The other human remains reported from the lower creek deposit were obtained in the extensive diggings carried on at the point marked *N* in Fig. 4. In the section at this point the lower fill shows extreme irregularity. This is assigned to subsequent scour and fill, evidences of which are more marked here than anywhere else in the sections exposed by the canal excavations. Cutting by the stream has been so pronounced that, in the midst of the area over which the bones are scattered, the lower deposit has at one point been completely removed, and the upper filling rests in a depression cut into formation No. 1 (the underlying marine beds).[3]

A few feet to the west of this more human bones were found along the contact line of formations Nos. 2 and 3 (the upper and lower creek deposits), or slightly within the basal portion of the upper creek deposit. Because of the close association of these two finds, because there is no duplication of parts, and because all the bones came from a large individual, Dr. Sellards believes that the bones mentioned in the last paragraph and referred to the lower fill and those here mentioned as found a few feet to the west along the contact of the two fillings, all belong to the same skeleton.[4] This may be called skeleton No. 2.

If these bones all belong to one skeleton, the fact that a part of them were found in formation No. 2, as interpreted by Dr. Sellards, and a part of them in the base of formation No. 3 requires explanation. This naturally led to the suggestion that those bones which were found in the basal portion of the upper fill reached that position by being washed out of the lower deposit.[5] If, however, one examines Fig. 6 of the Florida state report, it is seen that the bones

[1] Symposium, p. 17.
[2] *Ibid.*, p. 22.
[3] *Eighth Ann. Rept.*, etc., Fig. 6, p. 137.
[4] *Ibid.*, p. 142.
[5] Symposium, p. 54.

found in the basal portion of the upper deposit are *upstream* from the point where the bones in the lower deposit occur. Besides this, two out of the three bones are figured as occurring at a considerably higher level than the bones in the lower deposit. At the same time the attitude and appearance of these suggest that they had already moved somewhat down the rather steep slope implied by the depositional lines.

These suggestive relations occur at the most critical locality. It was here that most of the collecting was done, not only during this later visit, but also during the previous one. From the geological point of view this section is peculiar in that here there has been more obvious scour and fill by the stream than elsewhere. This is made evident by an unusual number of pockets and lenses of sand and muck, as well as rapid dovetailings of layers. It may be worthy of note also that the section here lies beneath the latest channel of Van Valkenburg's Creek. The pockets, "filled holes," lenses, and dovetailings render the identification of the true line between the lower and upper creek deposits both difficult and uncertain. While the line of division is reasonably distinct at most points elsewhere, as on the north bank already noted, it unfortunately becomes obscure in this critical section.

In the course of our examinations there frequently arose questions as to the line of division between the upper and lower deposits, and sooner or later the judgments of all members of the party were more or less involved in these efforts at discrimination. These questions revealed the fact that there were notable differences of opinion as to whether a given bit of a section belonged to the upper or lower deposit. If, as discussion and critical consideration proceeded, there was noticeable a tendency to shift the dividing line in one direction rather than another, it was to give the base of the upper creek filling a lower place in holes and hollows than it had been assigned before. In other words, there was a general disposition, as the result of progressive study, to lower the division line. This justifies the inference that any sharp division of the creek deposits in this portion of the south bank into distinct formations is lacking in complete conclusiveness.

A specific case of this kind of uncertainty is illustrated by Fig. 5. As a result of much digging for fossils at this point, the bank had gradually been cut back till, at the taking of this picture, it was perhaps 15 feet back from its original canal face. The entire thickness of the deposit from the base of the black muck and sand fill

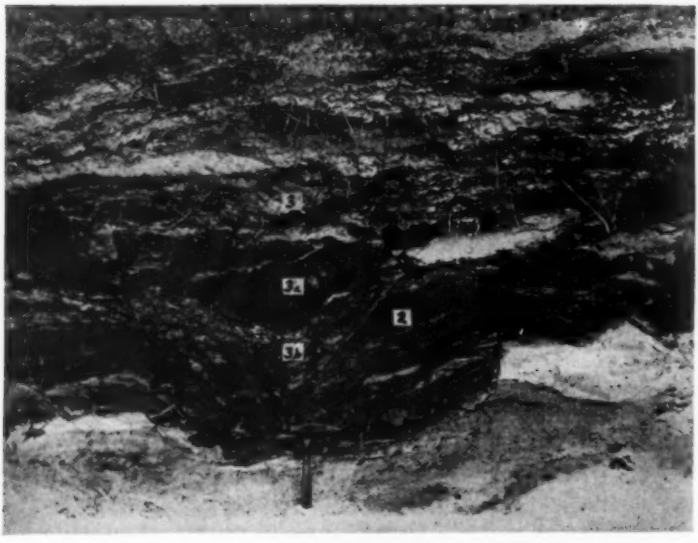

FIG. 5.—Section of south bank of the canal near point marked *N* (Fig. 4) as exposed by the party on March 21, 1917. At the base are buff marine sands with some shells (formation No. 1); No. 2 above is the lower creek fill which was originally supposed to extend up to the prominent line of white sand lenses, just beneath marker 3 in the middle of the picture; but upon more critical inspection, the patches of fill marked 3*a* and 3*b* were excluded from the lower fill and placed in the upper fill. No. 3 represents the unmistakable upper creek fill. It contains some small lenses and pockets of marine shells derived from formation No. 1.

(just to the left of the hammer) to the surface as it was in 1913, just prior to the excavation of the canal, is 5½ feet. As the party viewed the newly exposed section for the first time, all were ready to carry the upper creek filling down to the prominent line of whitish sands and reworked coquina shells just beneath marker 3 in Fig. 5. After a brief inspection, there seemed to be reasons for assigning the block

marked *3a* (Fig. 5) to the upper creek deposit. And then the upper deposit was extended downward to include the peculiar funnel-like fill marked *3b*, while the writer, at least, would hesitate to deny that the upper deposit might not, in reality, include also some of the material which reposes in lenslike fashion adjacent to this funnel. In any case it is clear that there was much scouring and filling at this point, and this involved the lower as well as the upper deposit. This suggests that the scour and fill arose from the course of the stream at this point—some turn, perhaps, or some configuration of its channel.

The peculiar funnel-like filling marked *3b* was so obvious as to suggest the name "funnel," as it was evidently a deep hole in the creek bed filled with alluvium. After the photographs were taken, further excavations were made, and at the bottom of the funnel the carapaces of two turtles were found. One of these, still firm and strong, has already been referred to (p. 676). With further horizontal digging into the bank the funnel quickly disappeared.

This particular locality has been a gold mine for bone-collecting, and far more excavating has been done here than at any other point. The writer suspects that one reason why this particular area has proved so prolific in results is that there was an exceptional reworking of material by the stream at this point, resulting in a greater concentration of bones, pottery, and coarser material. At the same time, this material was left in more unusual positions than in places where the stream action has been simpler. In fact, small lenses and stringers of shells derived from the erosion of the underlying marine coquina are frequently seen here, not only in the lower creek deposit, but in the upper creek deposit as well. If, then, the upper creek deposit has received an appreciable portion of its material from the more deeply buried marine beds, how much more of its material must have been derived from the far more accessible lower creek deposits which overlie these marine beds. The mixing of materials is obvious.

In view of the similarity of the upper and lower creek deposits, and the inevitable difficulty of drawing a perfect line of division between them; in view of the actual differences of opinion as to

just where such line should be drawn, and of changes of opinion once formed; in view of the natural doubt as to whether two such deposits measuring together only about six feet could in fact remain altogether unmixed and distinct; and in view of the observed fact that the stream, in its later action, actually did cut entirely through its own earlier deposits and into the marine formation below, it would seem that grave doubts as to the trustworthiness of correlations of this stream material may well be entertained. Perhaps it is obligatory that they should be entertained. The balance of evidence seems to lie in favor of including all doubtful horizons in the upper fill, since the upper fill does penetrate deep into the lower fill at so many points. The human bones and relics would seem to the present writer to belong to the upper creek deposit, which was contemporaneous with the human occupation of Florida. This interpretation would allow the correctness of Dr. Sellards' contention that the bones of the extinct vertebrates well down in the undisturbed part of the lower creek deposit are fossils primary to that deposit. With this revision of the stratigraphic view, the testimony of the inherent character of the human relics rises into scarcely less than decisive importance.

Now, among the human relics, the pottery seems to carry the most telling testimony as to the time when the aborigines dwelt on the banks of Van Valkenburg's Creek. The association of the pottery with the human bones may well be regarded as peculiarly significant, for the pottery was a human product and it carries a time relation. Fragments of pottery, in more or less abundance, were found on the second visit at as low a horizon in the creek deposits as were any of the human bones. The writer saw no evidence of any human race earlier than the pottery-makers, and no such earlier race has been claimed. Now, as MacCurdy,[1] Hrdlička,[2] and Holmes[3] have pointed out, the pottery belongs to the type which was used by the mound-building Indian tribes of Florida. Such pottery was in common use in the middle or later Neolithic age. This pottery, of itself, would not therefore be assigned a date earlier than mid-Recent. Even in Europe, where the presence and

[1] Symposium, pp. 60–62.

[2] *Ibid.*, pp. 47–50.

[3] *Ibid.*, p. 51.

development of man has been traced from the mid-Pleistocene on, the introduction of pottery by Neolithic man is not placed as far back as the close of the Glacial period and is not, therefore, Pleistocene as usually defined. There is no ground to suppose that pottery was in use in North America before it was in use in the Old World; more probably it was introduced here later.

If (1) the testimony of the human relics, particularly that of the pottery, be taken at its apparent paleontological value; if (2) the upper creek fill, whose accumulations demonstrably continued on until 1913, be regarded as embracing all the human relics, as seems quite consistent with the physical evidence; if (3) the critical extinct vertebrate fossils found in this upper creek fill be regarded as derivatives from the lower creek fill; and if (4) the lower creek fill be regarded as contemporaneous with the last living stages of the extinct vertebrates whose fossils it holds as primary inclusions, as Dr. Sellards contends, the whole history becomes consistent physically and paleontologically, and the gist of its lesson is that the Pleistocene fauna lived longer in this genial southern clime than it has been credited with in the more northern latitudes, while the evidence of man's presence here falls into harmony with the general tenor of other evidences which fail to assign him an antiquity beyond the mid-Recent.

ANOTHER LOCALITY OF EOCENE GLACIATION IN SOUTHERN COLORADO[1]

WALLACE W. ATWOOD
Harvard University, Cambridge, Massachusetts

Since the publication of the paper on the Eocene glaciation recorded at the northwest base of the San Juan Mountains near the village of Ridgway,[2] the author's attention has been called to a similar discovery made by Mr. Charles W. Drysdale in British Columbia at about the same time.[3]

When Eocene till was found near Ridgway, and the formation was given the name Ridgway till, it was anticipated that other glacial deposits of the same age would soon be recognized in other parts of the Rocky Mountain province. Each of the larger ranges in this great geographic province has had a history somewhat similar to that of the San Juan Mountains. These ranges were all uplifted, some as great anticlinal arches, some as domes, and others with some faulting and intrusion, at the close of the Mesozoic era or beginning of the Cenozoic time. Those great arches and domes were dissected into mountain forms, and, when favorable climatic conditions prevailed, glaciers probably formed in many of the higher basins among those mountains and assisted in the further dissection of the ranges. Now that Eocene till has been discovered in British Columbia, and at a locality to be herein described near the south margin of the San Juan Mountains, it appears to be well established that conditions favorable for the formation of Alpine glaciers did obtain in the western portion of North America during early Tertiary time.

[1] Published with the permission of the Director of the United States Geological Survey.

[2] W. W. Atwood, "Eocene Glacial Deposits in Southwestern Colorado," *U.S. Geol. Survey, Prof. Paper 95-B*, 1915.

[3] C. W. Drysdale, "Geology of Franklin Mining Camp, British Columbia," *Canadian Geol. Survey Mem. 56*, 1915.

The locality at which this most recent discovery of Eocene till in Colorado was made is about 20 miles southeast from Pagosa Springs and in the south-central portion of the Summitville quadrangle of the United States topographic atlas.

The deposit is exposed in the valley walls of White Creek where that stream is dissecting the surface of V Mountain. The best exposures may be reached by trail from the Blanco Basin, following the base of the bold mountain escarpment just east of V Mountain to a large lake held in by recent landslides, and thence westward half a mile to the junction of the two upper forks of White Creek.

The ridge between the two upper forks of White Creek and that west of the west fork are composed of this ancient till, but on their surfaces there are fragments of the later Tertiary volcanics that have fallen or been washed from the mountains to the east.

The till is composed of stones ranging up to 5 feet in diameter imbedded in a clay matrix. Many of the stones are distinctly striated, and most of them are subangular and beautifully polished and planated. The notable character of this till, however, is the abundance of stones that have come from the pre-Cambrian formations, now nowhere exposed near this locality, and the many bowlders known to have come from the Cutler or Dolores formations of Permo-Triassic age which must also be buried in the core of the range. Of equal significance is the absence of stones from the later Tertiary volcanics. These two points make it clear that the ice which deposited this till formed and accomplished its work during the time when the pre-Cambrian core of the range and the upturned Paleozoic and Mesozoic formations were exposed at the surface, and before the later Tertiary lavas and tuffs were present.

The stones in this till consist of granites, quartz, quartzites, schists, gneisses, jaspers, red sandstones from the Cutler or Dolores formations, and conglomerates from one or the other of those formations. There are also many porphyries and some bowlders of a tuff-breccia, just as there are in the type section of the Ridgway till. These igneous and volcanic rocks were derived from an earlier series of intrusives and eruptives and are quite distinct in age from the later volcanics which constitute the mass of the present mountains.

The lithological character of this drift is distinctly different from that of the three Pleistocene drift deposits which are so commonly found in the foothill regions bordering the San Juan Mountains, and which are all present in this immediate district. The Pleistocene glacial deposits are characterized by the stones of the later Tertiary volcanics and usually contain very little that could not have been derived from those volcanics.

In one exposure near the junction of the two forks of White Creek on V Mountain a pebble-clay till is exposed which resembles the upper member of the Ridgway till at the type locality. This pebble clay contains many stones less than one-quarter of an inch in diameter and a few cobblestones and small bowlders. The best striae were found on stones that were taken from this pebble-clay phase of the till.

Beneath this exposure of Eocene till is the Mancos shale, and in this respect the conditions are identical with those at the northwest base of the range. Upstream from the best exposures of the till an andesitic rock cuts the Mancos shale and appears to be at the base of the till for some little distance. On the slopes above this deposit of till there are beautifully waterworn pebbles of pre-Cambrian rocks similar to those that characterize the Eocene glacial deposit. They appear to have come from the complete disintegration of a conglomerate. Such a conglomerate overlies the Ridgway till at almost all of the known localities.

This section is somewhat less satisfactory than many of those described in the first report on Eocene glaciation in the San Juan Mountains, for it is not at present overlain by the later Tertiary volcanics. The lithologic character of this deposit determines its age.

Reviews

Eocene Glacial Deposits of Southwestern Colorado. By WALLACE W. ATWOOD. Prof. Paper, U.S. Geol. Surv., No. 95-B, 1915. Pp. 13–26, pls. 4, figs. 11.

Glacial deposits of Eocene age were discovered in 1913 near Ridgway, Colorado, northwest of the San Juan Mountains. The nine exposures are scattered over an area of 20 square miles. The Ridgway till rests on the Mancos shale and is overlain by the Telluride conglomerate and San Juan tuff. The till is divided into two members. The lower is a bowlder till containing many striated stones, some very large. The upper till is a dark slate-colored clay, unstratified and containing only a few striated pebbles. The bowlder till is believed to have been deposited by glaciers heading in the region of the present San Juans. The pebble till may have been deposited by ice moving over extensive surface exposures of Mancos shale from the region of the West Elk Mountains to the northeast.

The paper closes with a summary of the distribution of pre-Pleistocene glaciation. An extensive bibliography is appended.

H. R. B.

The Yentna District, Alaska. By STEPHEN R. CAPPS. U.S. Geol. Surv., Bull. No. 534, 1913. Pp. 75, pls. 13, figs. 7.

This area lies along the southeast base of the Alaska Range in the drainage basin of the Yentna River, a tributary of the Susitna. The oldest rocks are a pre-Jurassic series of slates and graywackes. They are everywhere faulted and folded, and are intruded by igneous rocks ranging from granite to diorite. The intrusives are provisionally assigned to the late Lower Jurassic or Middle Jurassic. Older dikes of diabase and greenstone have been deformed and metamorphosed along with the slate series.

Next younger are rocks of Eocene age, consisting of sands, shales, gravels, and commonly some lignitic coal. Coarse stream gravels overlie the coal-bearing series. Evidence of the Tertiary age of the gravels was obtained. They were formerly regarded as Pleistocene.

They are probably equivalent to the Nenana gravels on the north side of the Alaska Range.

Pleistocene and recent glaciation are described. The present snow fields and glaciers are confined to the heads of the valleys and the higher portions of the Alaska Range.

Placer gold was first discovered in the Yentna district in 1905. The total production up to 1911 was $383,000. The gold is believed to have been derived from quartz veins and stringers associated with the intrusions in the slate and graywacke series.

The coal, in beds ranging from 3 to 12 feet in thickness, is a medium- to low-grade lignite.

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